

NITROGEN UPTAKE AND LEACHING POTENTIAL OF
POLYMER-COATED N FERTILIZERS IN
A TURFGRASS ENVIRONMENT

By

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By

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Establishing and maintaining quality turfgrass requires nitrogen (N) fertilization. However, potential leaching losses of N present environmental and economic concerns. Nitrogen losses deprive turfgrass of an essential nutrient and serve as a potential pollutant to surface and ground waters. Studies were conducted to investigate the effect of polymer-coated $(\text{NH}_4)_2\text{SO}_4$ (AS), urea, and KNO_3 , with varied coating thicknesses and sizes, on uptake and leaching of applied N to bermudagrass (Cynodon dactylon) grown on sandy soil and the factors effecting the N release.

A laboratory study was conducted to investigate the effect of temperature, coating thickness, and N substrate on the release of N from the encapsulated fertilizers into deionized H_2O . An increase in temperature from 25°C to 35°C

increased N released from 30% to 56% for coated AS with 4.7% coating (CAS-4.7), and from 70% to 78% for coated urea with 4.8% coating (CUrea-4.8). Data suggest a differential increase in solubility of the N substrates. Increases in coating thickness reduced N release differently, depending on N substrate and granule size.

In a field study, using open-ended lysimeters equipped with multi-depth samplers, the N uptake and leaching of uncoated and polymer-coated ^{15}N AS and urea applied to bermudagrass growing on sandy soil were determined. Nitrogen uptake recovery using an ^{15}N tracer method and a difference method increased as a result of coating, except for CAS-9.8. Coated Urea-10 produced the highest N uptake, followed by CUrea-4.8 and CAS-4.7. Nitrate-N concentrations in the intermediate vadose zone (IVZ) at the 30 cm depth, and the saturated zone at 90 and 120 cm, were affected by applied N, coating and coating thickness.

In another lysimeter study, the N sources were applied to lysimeters packed with a sand-based golf green profile. Nitrogen uptake and N leached to the 46 cm depth were determined. Nitrogen uptake ranged from 26% (KNO_3) to 69% (CAS-7.5). Nitrogen leached from the CAS and CUrea treatments ranged from 0.3% (CAS-15) to 7.7% (CAS-7.5) of applied N.

This study documents the effectiveness of the polymer-coated N sources in minimizing N leaching and increasing N uptake in a turfgrass environment.

CHAPTER 1 INTRODUCTION

The turfgrass industry in the United States is a multi-billion dollar industry that is in demand of high quality turfgrass. Nitrogen (N) is one of the most important nutrients in turfgrass culture. Maintaining a high quality turfgrass often requires the application of large quantities of N for plant uptake (Snyder et al., 1984; Sartain, 1988). One of the primary goals of N management is to improve the use efficiency of applied N. Low efficiency of applied N is due to N losses from soil/plant systems through leaching and/or gaseous losses during the growing season (Bock, 1984). There is a growing concern that N fertilizers are potential nitrate (NO_3^-) pollution sources, contaminating groundwater and surface waters. Nitrate is, in fact, considered to be one of the most widespread groundwater contaminants (Pye et al., 1983). Leaching of nitrate from fertilizers applied to turfgrass areas is proposed to be a major source of groundwater pollution in areas where turfgrass is a major land use (Flipse et al., 1984).

Attention is focused on the leaching of NO_3^- from N fertilizers for two main reasons: first, NO_3^- is the most mobile form of N, and will move freely with the soil solution

if not taken up by the plant; second, its presence in drinking water supplies in excess of EPA-established drinking water standards (10 mg/l NO_3^- -N) presents health hazards (Exner et al., 1991). Leaching potential may be minimized or eliminated through the use of available technology and management practices.

Optimizing plant uptake and minimizing N losses may be accomplished through the use of controlled-release N sources. Recent advances in polymer coating technology has resulted in production of thin layer polymer-coated N fertilizers such as reactive-layer coated N sources. The thin-layer coating makes these products more cost effective and the nature of the polymer and its reaction with the N substrate makes the coating less susceptible to physical and microbial degradation. Information is needed regarding the effectiveness of controlled release N fertilizers such as reactive-layer coated N fertilizers in optimizing uptake efficiency and minimizing leaching potential of applied N in turfgrass environments.

The objectives of this study were:

- 1) to quantify plant uptake of N from applied polymer-coated N fertilizers;
- 2) to monitor NH_4 -N and NO_3 -N concentration in the intermediate vadose zone (IVZ) and the saturated zone;
- 3) to determine and quantify the effect of N sources and varying coating thicknesses on NH_4 -N and NO_3 -N leaching through a golf green profile; and

- 4) to evaluate the effectiveness of coating thicknesses in assuring N supply to turfgrass and minimizing leaching losses.

CHAPTER 2 LITERATURE REVIEW

Fate of Nitrogen in a Turfgrass Environment

Understanding the nitrogen (N) cycle is paramount for maintaining a high quality turfgrass while minimizing the effects of N fertilization on the environment. Fate of N in a turfgrass environment includes several major categories of the N cycle. These include: 1) plant uptake; 2) soil retention and microbial immobilization; 3) runoff and leaching into groundwater and surface waters; and 4) losses to the atmosphere (Petrovic, 1990). Figure 2-1 is an illustration of the N dynamics which occur in a turfgrass ecosystem.

Nitrogen Transformations in the Soil

There are two basic forms of N within the soil: organic and inorganic. Nitrogen can also undergo numerous reactions, with the primary soil reactions including mineralization, immobilization, nitrification, denitrification and volatilization (Tisdale et al., 1993).

Through the process of mineralization, organic N present in the soil is transformed by soil heterotrophic microorganisms to NH_4^+ . The NH_4^+ produced during mineralization or supplied through fertilization may take a variety of paths.

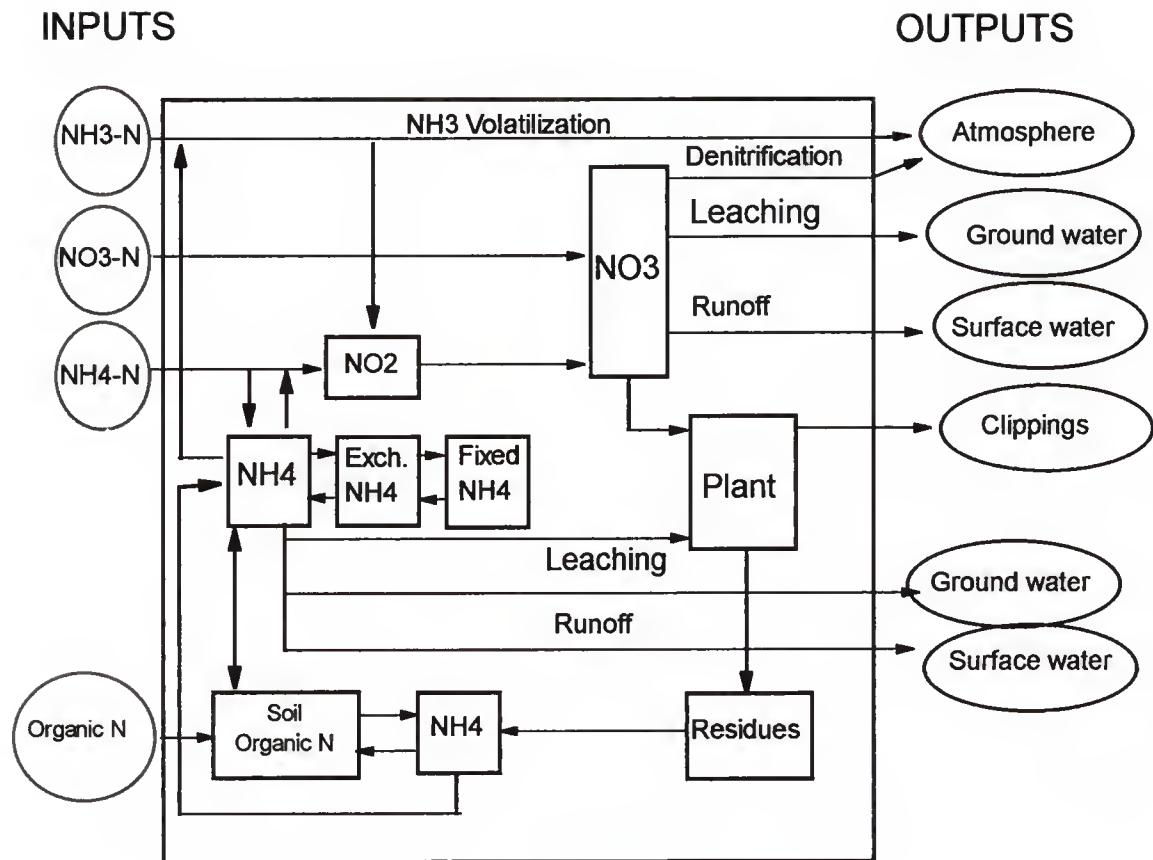


Figure 2-1. Nitrogen cycle in a turfgrass ecosystem (Petrovic, 1990).

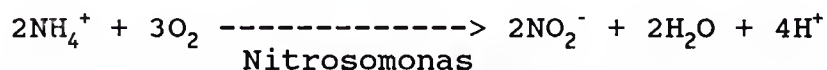
It may be oxidized to NO_2^- and then to NO_3^- during the process of nitrification, it may be taken up by plant, it may be further utilized by microorganisms in the soil, it may be "fixed" in the interlayers of clay minerals, or it may be lost to the atmosphere at high pH through the process of volatilization (Tisdale et al., 1993).

Inorganic N present in the soil or produced by mineralization can also be used by soil microorganisms through microbial immobilization. Soil microorganisms require both carbon (C) and N to grow and multiply. When an organic material with a high C:N ratio is incorporated into the soil, soil microorganisms use the readily available N for their growth processes. This immobilized N is temporarily tied up and is unavailable for plant uptake (Paul and Clark, 1989).

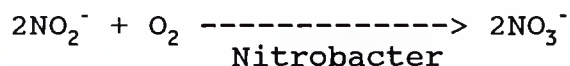
Starr and DeRoo (1981) studied N immobilization and uptake by a mixture of Kentucky bluegrass (Poa pratensis L.) and red fescue (Festuca rubra L.) in a 3-year field study using labeled and unlabeled N source at $195 \text{ Kg ha}^{-1}\text{yr}^{-1}$ for the first 2 years and 180 Kg ha^{-1} for the third year. They reported uptake of 20% from the first fertilizer application and 35% from the second application. Most of this uptake occurred within 2 to 3 weeks after application, with uptake falling to near zero after that. They suggested that large amounts of fertilizer N were immobilized in the thatch by the microbial population associated with this layer. This resulted in low total efficiency of fertilizer N uptake into

the above-ground portion of the grass. Watson (1987) also conducted a study wherein the effect of immobilization on N recovery by perennial ryegrass was observed. Seven weeks after the application of N, 13% of applied urea was found in the soil organic N pool compared to 17% in the case of NH_4NO_3 .

The two-phase process of nitrification also plays a significant role in the fate of N. Ammonium is first oxidized to NO_2^- . This reaction can be represented by (Tisdale et al., 1993).



The second phase involves further oxidation of NO_2^- to NO_3^- in a reaction represented by the following.



Since microbial activity is involved in the nitrification process, the rate and degree of nitrification are greatly influenced by soil temperature, moisture, Ph, microbial population, and supply of NH_4^+ . The NO_3^- produced by nitrification may also take different paths. These paths include plant uptake, assimilation by microorganisms, leaching, or denitrification and resulting loss to the atmosphere (Tisdale et al., 1993).

Denitrification is the process of reduction of NO_3^- to gaseous forms of N (N_2O , NO , and N_2) by soil microorganisms. The rate of denitrification is affected by several factors. It generally occurs where oxygen (O_2) is absent or present in

only low concentrations, such as when the soil is moist and has a high water holding capacity, in aggregates which are water saturated, or near sizeable clumps of actively decomposing organic material. Carbon is also a necessary component of the denitrification reaction. Thus, it is typically assumed that denitrification does not occur at an appreciable rate in groundwaters (Firestone, 1982).

Another mechanism for gaseous loss of applied N is through the process of ammonia (NH_3) volatilization. This path of N loss may be significant when urea fertilizers are used. The rate at which NH_3 is volatilized is dependent on pH and urease enzyme activity, which hydrolyzes urea to ammoniacal form (Torello et al., 1983). Torello et al. (1983) reported that NH_3 volatilization rates were reduced when sulfur-coated urea was used, compared with uncoated urea. Losses were also smaller from prilled urea than from liquid urea which was spray applied. In another study, Torello and Wehner (1983) reported volatilization losses of 39% for urea applied to thatch and 9% for urea applied to soil cores.

The interaction of these processes constitutes the study of fate and transformations of N complex. Studies of the distribution of N in a turfgrass environment are limited. Most studies in this area have further limited to individual paths of N. More research is needed to investigate the fate and transport of N in a turfgrass ecosystem as a whole.

Nitrogen Uptake

Nitrogen is an essential nutrient for turfgrass growth and maintenance. Thus, plant uptake is a major sink for N. Plants absorb N in the forms of NH_4^+ and/or NO_3^- (Barracclough and Smith, 1987). However, NO_3^- can normally be found in higher concentrations in agricultural soils than NH_4^+ because of nitrification (Tisdale et al., 1993). Ammonium-N, on the other hand, is a preferred source of N by some plants because internal energy is saved when this form of N is taken up by the plant (Taiz and Zeiger, 1991).

Efficient N management for optimum plant growth and protection of the environment requires increasing use-efficiency of applied N, for example, optimization of plant uptake. However, plant uptake of N is affected by numerous factors. These include N available for uptake, N source and rate, soil moisture and temperature, and plant species (Petrovic, 1990).

Amount and form of available N affect plant uptake. Barracclough et al. (1985) studied N uptake of ryegrass using single- and double-labeled ^{15}N NH_4NO_3 . The results of their 3-year study showed that average annual recoveries of N were 99, 76, and 50% of applied N at 250, 500, and 900 Kg ha^{-1} , respectively. They also found that at 250 Kg N ha^{-1} , about 70% of the N in the crop was derived from the ammonium pool compared with 64 and 59% at 500 and 900 Kg N ha^{-1} , respectively. They suggested that, at the lower application rates, preferential

uptake of ammonium was occurring. However, as N supply exceeded crop requirements, nitrate became the major N source.

Plant species also take up N in varying amounts and at different rates. Plants differ in the amounts of N they require for growth and maintenance. In comparing the study conducted by Barraclough (discussed above) with a study conducted by Sheard et al. (1985), differences in N uptake by different plant species were observed. Sheard et al. reported a recovery of 60% of the applied N during season-long clipping trials of Penncross creeping bentgrass (Agrostis palustris Huds.) when fertilized at 240 to 287 kg ha⁻¹ yr⁻¹.

Nitrogen source, in particular, plays an important role in N uptake efficiency. Numerous studies have investigated the effect of different N fertilizers on plant uptake. Mikkelsen et al. (1994) investigated the uptake efficiency of selected controlled-released fertilizers (CRF). They reported that both N application rate and fertilizer source had a significant effect on the N concentration of stems and leaves. Plants receiving a daily application of NH₄NO₃ had the highest tissue N concentration for the entire experiment, with the results for other materials decreasing in the following order: NH₄NO₃ > SCU > Osmocote > Prokote > IBDU > Ureaformaldehyde > Oxamide. Among the controlled-release sources tested, coated N fertilizers were more effective in increasing tissue N concentrations than uncoated sources when averaged over the entire experiment. In another study conducted by Watson

(1987), two water-soluble N sources, urea and NH_4NO_3 , were applied to perennial ryegrass to evaluate N uptake. He reported that 53% of applied N from NH_4NO_3 was recovered in the clippings, compared to 31% recovery from urea.

It is the interaction of these factors which determines net uptake of N. Best management practices should take into consideration the relative weight of each factor affecting uptake at specific turfgrass locations.

Leaching of Applied Nitrogen

Total world consumption of fertilizer N in 1990-91 was 78 million tons per annum, with a projected yearly increase of 2 to 3% (Shaviv and Mikkelsen, 1993). Golf courses alone account for more than 1.3 million acres of managed turfgrass in the United States (Cohen et al., 1993), requiring approximately 300,000 tons of N annually. Once N is added to the soil, it undergoes various transformations within the N cycle, including nitrification. If nitrate is not taken up by the plant, it may move below the root zone. Once below the root zone, it will eventually leach into groundwater, thereby contaminating groundwater and surface water supplies. Thus, groundwater quality has become a focal point of concern with regard to N fertilization and management.

Numerous studies have shown that the most common source of nitrate pollution of groundwater and surface waters is agriculture (Halberg, 1987; Keeney, 1982; Pratt, 1984). Much of the nitrate pollution arising from agricultural use

can be attributed to heavy fertilization in intensively row-cropped settings, in intensively irrigated-grain agriculture, in the irrigation and fertilization of shallow-rooted vegetable crops, and locally in intensive animal feeding and handling operations (Keeney, 1986). Leaching in relation to fertilization/nutrient management has been documented as well for golf courses and home lawns (De- Roo 1980; Keeney, 1986; Morton et al., 1988).

Groundwater is a major source of drinking water in the United States (CAST, 1985), with nitrate pollution of groundwater being steadily on the rise (Hallberg, 1987). This rise in nitrate contamination has caused concern over potential health hazards associated with this type of groundwater pollution. Nitrate accumulation in groundwater becomes a health risk when the water is subsequently consumed in high enough amounts by humans and animals. These health risks include methemoglobinemia, cancer, and possibly others (CAST, 1985; Keeney, 1986). For these reasons, public health standards for nitrate in public drinking water supplies in the U.S. have been set by the United States Environmental Protection Agency (EPA) at $10 \text{ mg L}^{-1} \text{ NO}_3\text{-N}$ (Keeney, 1986).

Nitrate is a highly soluble and very mobile plant nutrient. It is these qualities that facilitate plant uptake. However, nitrate's high solubility and mobility also make it very susceptible to leaching through the soil (Keeney, 1982). Nitrate can enter ground water and surface waters from a

variety of natural and human sources. Natural sources include soil N, N-rich geologic deposits, and atmospheric deposition (Madison and Brunett, 1985). Human sources include fertilizer application, feedlot drainage, dairy and poultry production, mineralization of N by cultivation, and leaching of soils as a result of the application of irrigation water (Madison and Brunett, 1985). Once N is converted to nitrate in the soil, it remains in nitrate form unless it is removed by plant uptake, denitrified or leached.

There are two main mechanisms that control the movement of nitrate through the soil. The first and most important mechanism is convection or mass flow of nitrate with moving soil solution. A second mechanism of transport is by diffusion. Diffusion involves the process whereby solute become less concentrated under the influence of molecular-scale collisions. However, under saturated conditions, convection is the main mechanism for nitrate transport to the ground water. Diffusion is limited to relatively small distances (e.g. near plant roots) compared to convection (Keeney, 1986).

Nitrate movement within the soil is affected by many factors. These include spatial variability, soil type, infiltration rate, irrigation rate, N source and rate, and climate (Keeney, 1986; Peterson and Frye, 1989). Spatial variability in the soil affects the rate at which nitrates will be transported through the soil in any given area. For example, a single worm hole, decayed-root channel, or restric-

tive layer of soil can drastically effect the rate at which nitrate is leached. Thus, spatial variability makes it very difficult to determine infiltration rates for large areas. Van de Pol et al. (1977) conducted a study to investigate the impact of spatial variability on infiltration rates. They added a pulse of chloride to water applied to a clay soil by steady-state trickle irrigation, and monitored downward movement of the pulse at 24 locations in an 8 m x 8 m field plot. Even though the application rate was uniform, they observed a log-normal distribution of apparent vertical solute velocities, with a coefficient of variation of 61%.

Soil type also greatly influences nitrate leaching rates. Soils have long been known to evidence vertical and horizontal variability in their chemical, physical, and biological properties (Keeney, 1986). Biological and physical factors interact strongly to affect many processes involved in nitrate leaching. For example, soil texture and structure affect water and oxygen diffusion, thereby affecting in turn the presence of anaerobic microsites along with subsequent denitrification rates and amounts (Keeney, 1986). Variability also affects water infiltration rates, leaching rates, and biological transformations including plant uptake and mineralization.

Reike and Ellis (1974) conducted a study to investigate NO_3^- movement in a sandy (91% sand) soil profile. They applied 290 kg N ha^{-1} as NH_4NO_3 each spring for two years, with

periodic soil samples being taken to a depth of 60 cm. Fertilizer N application increased NO_3^- concentrations at the 45 to 60 cm depth when compared with unfertilized plots on only two of 20 sampling occasions during the study. However, soil NO_3^- levels were elevated at a depth of 30 cm for the fertilized plots throughout the experiment.

Infiltration rates also play an important role in nitrate leaching, because nitrate normally moves with percolating water. Therefore, the rate and direction of nitrate movement in the soil is roughly related to the concentration of the nitrate in soil solution, as well as, the direction and rate of water movement (Keeney, 1986). Infiltration rates are affected by many factors including soil slope, vegetative or plant cover, stability of soil aggregates, amount (antecedent level) of soil water at the start of a rainfall event, and all factors affecting the size and continuity of soil pores (Peterson and Frye, 1989).

Dowdell and Webster (1980) conducted a lysimeter study to investigate leaching losses of fertilizer N applied to perennial ryegrass. They applied 400 kg N ha^{-1} of calcium nitrate labeled with ^{15}N . Approximately 2 to 5% of the ^{15}N was lost to drainage in the winter after application. Losses due to drainage in subsequent years were drastically diminished, only accounting for about 0.1% of the ^{15}N . Concentrations of nitrate ranged between 4 and 16 mg N L^{-1} .

Irrigation and rainfall have a direct impact on leaching

of nitrate. Most leaching occurs when soil moisture exceeds evapotranspiration rates (Peterson and Frye, 1989). Snyder et al. (1984) investigated the effect of irrigation and N source on leaching of N from a sandy profile covered with bermudagrass. Ammonium nitrate and sulfur-coated urea (SCU) were applied at a rate of 98 kg N ha⁻¹ to their plots. Each plot was then irrigated either on a standard daily schedule or by tensiometer-activated irrigation. Nitrogen was also applied in the irrigation water, and samples of soil water were taken daily. Samples were analyzed for the amount of N leached past the root zone. Results showed that 0.3 to 56% of the applied N had leached. These results were highly influenced by irrigation schedule, N source, and time of the year. February and March evidenced the highest leaching, with less in April and May and the least in June and July. Snyder et al. (1984) concluded that the decline in leaching was most likely a result of increased plant growth and evapotranspiration rates, with irrigation rates also heavily influencing leaching losses. Leaching losses were 2 to 28 times higher for plots irrigated on a daily schedule than for plots coupled to tensiometer sensor. Plots with the NH₄NO₃ treatment had a leaching rate 2 to 3.6 times higher than plots with the SCU treatment.

Nitrogen source and rate play a critical role in the leaching of nitrate to the groundwater. Numerous studies have been conducted to investigate the impact of slow-release

fertilizers in reducing leaching potential. Mikkelsen et al. (1994) conducted a greenhouse study to evaluate N leaching loss of six controlled-release N fertilizers and one soluble N fertilizer on container-grown Euonymus patens Rehd. They reported that coated fertilizers generally had less leaching losses compared to the non-coated fertilizers. Daily application of NH_4NO_3 resulted in a constant rate of N loss. After the first two weeks following fertilizer application, virtually all of the leached N was in the NO_3^- form. Nitrogen leaching losses were all increased by doubling the fertilizer application rate from 1 kg N m^{-3} to 2 kg N m^{-3} . Total N leaching losses from all sources were greater during the first 15-week period following fertilizer application, and were determined to represent as much as 24% of the applied N. However, in the 11-week period following a second fertilizer application, total N leached was determined to be less than 11% of the applied N.

The rate at which N is applied to turfgrass also affects the amount of N leached. Exner et al. (1991) conducted a study to investigate deep nitrate movement in the unsaturated zone of a simulated urban lawn fertilized with different rates of N. In this study turfgrass plots were treated with NH_4NO_3 at rates of 0, 1.0, 1.5, 2.0, and $2.4 \text{ kg N } 100 \text{ m}^{-2}$. The turf received approximately 640 mm of water during the 34-day study. The researchers reported that as much as 95% of the nitrate applied in late August leached below the turfgrass

root zone. They also reported that nitrate concentrations in the leachate ranged from 34 to 70 mg L⁻¹ NO₃⁻-N.

There are many management practices which help to control N leaching and consequently reduce groundwater contamination. These practices include selecting the best N source, applying appropriate N rates, proper irrigation scheduling and maintenance of good soil cover (Peterson and Frye, 1989). Numerous studies have been conducted to investigate the effectiveness of differing management practices. Shirmohammadi et al. (1991) studied the long-term effects of different management practices on nitrate N loadings to a shallow, unconfined, groundwater system. Two representative watersheds in the coastal plain physiographic region of Maryland were selected for this study, with soils in these watersheds having moderate infiltration capacity. Results from their study indicated that best management practices (BMPs) used in conjunction with winter cover (barley) reduced nitrate leaching to a groundwater system. They also found that turfgrass reduced surface runoff of water and N, while increasing leaching losses of water and nitrate N.

Other Losses of Nitrogen

Other potential losses of N in a turfgrass system include sediment losses and runoff. However, sediment losses and runoff from turfgrass sites are minimal. Gross et al. (1990 and 1991) investigated the effect of liquid and granular fertilizer N on runoff volume and sediment losses from various

tall fescue (Festuca arundinacea Schreb.) mixed with Kentucky bluegrass. Runoff losses of total N were higher from the liquid and granular treatments than from the control plots. However, there were no differences between treatments. The results of their studies also indicated that nutrient and sediment losses from turf via runoff is very low compared with agronomic row crops.

In another study conducted by Watschke, runoff from turfgrass sites was investigated (Petrovic, 1990). The results from silt loam turf sites with slopes ranging from 9 to 12% showed that one rainfall event produced runoff during the two year study.

USGA Golf Green Profile

Leaching may be a problem for many sports turf sites. Golf greens, in particular, have a high potential for leaching because of the accompanying high sand profile which is designed for rapid removal of excess water. Golf course green construction utilizes multiple soil layers in order to optimize soil moisture retention and water movement. The United States Golf Association (USGA) recommends the use of a 30.5 to 35.5 cm sand-based topsoil overlying a 5 to 10 cm coarse sand (choker) layer and a 10 cm gravel bed with underlying tile drainage (McCarty and Cisar, 1993). These multiple layers are designed on the basis of the physics of layered soils to optimize moisture content of the root zone

mix and water flow through the golf green profile and into the drainage system.

Each layer serves a specific function in the retention and movement of water through the profile. The root-zone mix layer is designed for a relatively high infiltration rate. The moisture content of this layer then increases as it approaches the choker layer. As the moisture content increases it creates a near-saturated zone, generally referred to as the "perched water table" zone. The perched water table zone is, therefore, a part of the root-zone mix. The depth of this zone is a function of the texture of the root-zone mix layer relative to the choker layer's texture and depth (McCarty and Cisar, 1993).

The choker layer or coarse sand layer has multiple functions. This layer is designed to prevent migration of finer texture root zone mix into the gravel layer. However, its primary function is to regulate water flow into the gravel layer and subsequent flow into the drainage tiles. The choker layer is responsible for creating the perched water table as well (McCarty and Cisar, 1993). This plays an important role in regulating the water content of the root-zone mix layer. However, the necessity of this intermediate layer of coarse sand has been questioned.

The gravel layer has several functions in the golf green profile. This layer is responsible for the rapid movement of infiltrating water to the tile lines. The gravel layer also

helps prevent a rising water table from saturating the root zone and preventing salt movement from the subsoil into the root zone. Additionally, it acts as a buffer between the moist root zone and dry sub-grade soil, preventing the dry sub-grade soil from extracting water from the root zone. Finally, if an intermediate choker layer is not used, the gravel layer serves the functions of the intermediate choker layer as well (McCarty and Cisar, 1993).

Rapid removal of excess soil water is a vital attribute of putting greens. Drainage tiles have been embedded in the gravel layer for the removal of this excess soil water. Drainage tiles help prevent the greens from holding too much water under heavy rainfall or over-irrigation conditions. This helps in turn to minimize soil compaction and protect the golf green (Unger, 1971).

Several studies have been conducted in order to assess plant uptake and leaching characteristics in this type of profile. Brown et al. (1982) conducted a study investigating the interaction of N sources and soil texture in effecting nitrate leaching from a USGA golf green profile and a sandy loam soil green profile covered with bermudagrass. Leaching losses were 22% from NH_4NO_3 , 9% from activated sewage sludge, and less than 2% from IBDU and ureaformaldehyde where the root-zone mixture contained more than 80% sand. On the other hand, greens constructed with sandy loam soil had losses of 9%, 1.7% and less than 1%, respectively.

Gaines and Gaines (1994) also conducted a study to investigate NO_3^- retention by USGA greens mixtures compared to other soil textural sequences. Samples of sand, USGA greens mixture, loamy sand, and sandy clay loam, were used to compare nitrate retention by the several materials. Their results showed that soil texture affected the retention of NO_3^- -N in the sand, which absorbed the least amount of NO_3^- -N by 119 mg kg^{-1} , followed by the USGA greens mixture at 125 mg kg^{-1} , loamy sand at 149 mg kg^{-1} , and sandy clay loam at 173 mg kg^{-1} . They also reported that more NO_3^- -N was released from the first 50 ml of sand percolate (at 63%), followed by the USGA greens mix percolate at 58%, loamy sand percolate at 46%, and sandy clay loam percolate at 37%.

High-sand golf green profiles require improvement in nutrient and water retention. Through the use of the proper selection of fertilizer materials such as controlled release nutrient sources, NO_3^- -N leaching can be reduced.

Nitrogen Fertilizers

Sources of N used for turfgrass production and maintenance are numerous and have widely varying release characteristics. In general, N sources can be divided into two categories. The first category includes soluble N sources which are generally referred to as "quickly available N". The second category includes insoluble organic and soluble encapsulated N sources, which are generally referred to as "slow-release or controlled release N".

Soluble N Sources Quick-release N is water soluble and usually contains N in the form of NO_3^- or NH_4^+ . As discussed earlier, NO_3^- is readily available for plant uptake but is also very susceptible to leaching through the soil. Ammonium N is less likely to leach but is also rapidly transformed to NO_3^- through the process of nitrification. Quickly-available N sources require more frequent application in order to maintain turfgrass at a high quality. The products classified in this fertilizer group include soluble organics such as urea, and soluble inorganic salts such as $(\text{NH}_4)_2\text{SO}_4$ and NH_4NO_3 .

Urea is a product commonly used in the turfgrass industry. It is a water-soluble organic compound, containing 45 to 46% N. Before the N can be absorbed by the turfgrass it must undergo hydrolysis. Urea hydrolysis is an enzymatic reaction carried out by urease which transforms the N into NH_4^+ within a few days (Turner and Hummel, 1992)

Numerous studies have been conducted to determine the characteristics of this product. Studies have found that urea has a rapid release rate but is available for plant uptake only for a short time (Landschoot & Waddington, 1987; Mosdell et al., 1986; Spangenberg et al., 1986). One disadvantage associated with urea is its high foliar-burn potential (Johnson & Christians, 1984; Moberg et al., 1970). In a study conducted by Wesley et al. (1985), the rate of urea hydrolysis was investigated. They found that maximum N uptake occurred

within 24 hours after urea application with the recovery rate of applied N being 31 to 61% after 72 hours.

The most common inorganic salts used by the fertilizer industry include $(\text{NH}_4)_2\text{SO}_4$ and NH_4NO_3 . Inorganic salts have a high salt index which results in a high potential for foliar burn (Monteith & Bengston, 1939). Like urea, inorganic salts are quickly available for plant uptake but have a limited duration as such (Waddington et al., 1985). Most of the N applied is taken up by the plant within 4 to 6 weeks after N application (Starr and DeRoo, 1981)

Many studies have been conducted to investigate the effects of different inorganic salt fertilizers. In a study conducted by Sartain (1985), the effect of $(\text{NH}_4)_2\text{SO}_4$ on thatch buildup was investigated. He found that thatch accumulated most quickly when $(\text{NH}_4)_2\text{SO}_4$ was used as the N source, and concluded that thatch buildup was the result of the acidifying effect of $(\text{NH}_4)_2\text{SO}_4$ and consequent reduction in microbial activity.

Controlled-Release Fertilizers (CRFs) The terms "controlled-release" and "slow-release" fertilizers are often used interchangeably. However, a distinction can be made between these two N sources. Controlled-release fertilizers are generally synthetic organic N sources with low solubility and/or encapsulated synthetic organic or inorganic N sources. The rate of N-release from CRFs can be manipulated by varying the degree of solubility, particle size, and nature and

thickness of the coating used for encapsulation. Environmental factors may influence the rate of release but do not control it. Slow-release fertilizers (SRFs), on the other hand, encompass a variety of natural organic sources, with an release rate controlled by microbial activity and environmental factors affecting the N mineralization of these materials (Turner and Hummel, 1992).

Both SRFs and CRFs have been utilized in turfgrass production and maintenance for many years. Golf courses and nurseries, in particular, have utilized these materials to help satisfy their need for a long-lasting N source with a lower potential for leaching. The agronomic properties of these N sources have been investigated and are well-documented (Carrow and Johnson, 1989; Landschoot and Waddington, 1987; Sartain, 1990; Waddington and Duich, 1976; Woolhouse, 1974). In general, these materials extend the supply of N to the plant and support a steady rate of growth compared to quickly-available sources of N. This has three advantages. First, the N source does not have to be applied as frequently. Second, the response to applied N and consequently the quality of turfgrass is maintained for a longer period of time. Finally, losses of applied N may be reduced (Turner and Hummel, 1992).

Numerous studies have been conducted comparing and assessing the benefits from SRFs and CRFs. Sartain (1985) conducted a study comparing milorganite, a SRF, with $(\text{NH}_4)_2\text{SO}_4$

and IBDU (a synthetic organic CRF). He found that, when milorganite was used, the quality of bermudagrass was not affected by N source when compared with IBDU and $(\text{NH}_4)_2\text{SO}_4$. However, growth rates and N recovery were higher for IBDU and $(\text{NH}_4)_2\text{SO}_4$ compared to milorganite. In contrast, Barrios et al. (1982) evaluated the effects of milorganite in warmer climates, where milorganite produced higher growth rates and N recoveries when compared with other quickly-available and slow-release fertilizers.

Arminger et al. (1948) evaluated the response of turfgrasses to urea-formaldehyde (UF), a synthetic organic SRF. They suggested that the response of turfgrass is highly dependent on the ratio of urea to formaldehyde, and found that ureaform produced with a 1.3:1 ratio (38% N, 65 to 70% water insoluble) was slowest to release in the field.

Hummel (1989) evaluated four Escote RCUs with release rates of 70, 100, 150, and 270 days. Turfgrass response was highly correlated with release rates with the 70 day material producing the most rapid response with the shortest duration. The 270 day material released its N too slowly to produce a turf of acceptable quality.

Controlled-release and slow-release fertilizers should grow in demand in the future, not only for their agronomic benefits but, more importantly, for their place in nutrient management strategies and environmental pollution control. Snyder et al. (1984) investigated the influence of N source

and rate on leaching potential of N applied to a sandy profile. The higher rate of 78kg N/ha applied bimonthly, had leaching losses of 9.3 and 5% of the applied N from calcium nitrate and IBDU, respectively. Ureaform, SCU and urea leached less than 1% of the total amounts applied. Low leaching losses from urea were suspected to be a result of high volatilization rates on the alkaline soils to which the urea was applied. In another study conducted by Sartain (1990), selected SRFs were investigated to determine their N-release and leaching characteristics. He found that the form of N leached and the rate at which it leached depended on the substrate and solubility of the material. The quantity of N leached during this experiment was lowest for nitroform (33%) and highest for reactive-layer coated urea (RLCU) (95%), with intermediate rates for coated ammonium sulfate (88%), Nutra-lene (81%), sulfur-coated urea (SCU) (75%), and IBDU (52%). Substantial quantities of NO_3^- were not present in the leachate until after 64 days. This suggests, that the absence of NO_3^- prior to 64 days was the result of the absence of any plants, and subsequent rhizosphere microbial populations, in the experimental pots. While the environmental importance and benefits of SRFs and CRFs are believed to be significant they have not been fully assessed. More long-term studies need to be conducted to further evaluate the environmental impacts of these materials.

Fertilizer Recovery Methods

Efficient N management requires an understanding of the fate of applied N in the soil/plant system. The recovery and quantification of applied N fertilizer is a difficult task, due to the dynamic nature of the N cycle in the complex soil/turfgrass system. Numerous research has been conducted to evaluate and compare different methods of N recovery in the soil/plant environment. The most common techniques employed include the use of lysimetry, ceramic cup samplers, soil core sampling, and the difference and tracer methods of calculation (Keeney, 1986).

Lysimetry

The use of lysimetry is an important research tool used to investigate the fate of N under a range of management practices, soil types and turf varieties. A lysimeter is a container which physically isolates a soil/air/water environment hydrologically from surrounding soil (Bailey, 1984). There is no set design for lysimeters. Their design varies with the intended purpose, as they can be used to address a variety of research objectives.

There are two main types of lysimeters: weighing and percolation lysimeters. Both types have several subtypes within the category. For instance, weighing lysimeters include the hydraulic load-cell type (Hanks and Shawcroft, 1965), a floating type (King et al., 1956), mechanical weighing systems with automatic readout (Harrold and Dreibelb-

is, 1958), and strain gauge load cells (Sammis, 1981). Weighing lysimeters vary greatly in size and expense. Weighing lysimeters can be as simple as pots that are weighed at various time intervals, or as complex as lysimeters equipped with automatic weighing scales, moisture sensors and drainage systems. The cost can vary from as little as the price of a plastic pot to as much as \$16,000 each (Keeney, 1986).

Percolation lysimeters also vary in size and price, according to research objectives. These types of lysimeters are most often used to measure solute leaching. De Nobili et al. (1992) conducted an ^{15}N field study using lysimetric tanks to investigate the fate of oxamide and urea applied to turfgrass. Initial N absorption, during the first 40 days after fertilization, was higher for urea (23.5%) than for oxamide (12.1%) but after 64 days, absorption efficiencies were similar (11%) for both fertilizers. Leaching was much greater from the urea-fertilized soil (1.57 g) compared with losses from oxamide-fertilized soil (0.05 g). Total N fertilizer remaining in the soil at the end of the experiment was 27% of the applied urea and 40% of the applied oxamide.

Ceramic Cup Samplers

Ceramic cup samplers have also been used to monitor soil water since the early 1900's (Debyle et al., 1988). The use of ceramic cups has been established as a research tool for sampling soil solutes in the saturated and unsaturated (vadose) zone. A tube is attached to the end of the ceramic

cup and suction is applied, causing water to completely fill the pores of the ceramic cup and drip into its interior. In order to construct a device that will sample soil water in the vadose zone, it is necessary to use a porous cup that contains pores small enough so that the air in the soil, under atmospheric pressure, cannot enter even though a full vacuum is created within the sampler (Everett and McMillion, 1985). Under these conditions, only water from the capillary spaces in the soil will flow through the pores in the porous cup and into the sampler (Everett and McMillion, 1985).

Many studies have been conducted utilizing ceramic cup samplers to measure nutrient contents of soil solutions. For example, Hook and Kardos (1978) and Hook and Burton (1979) estimated nitrate loss below the root zone at municipal sewage irrigation sites using porous cups. Mansell et al. (1980) also utilized ceramic cup samplers to measure the effect of shallow and deep tillage on solute movement beneath citrus.

Difference Method

Recovery of applied N fertilizer by the plant can be estimated using the difference method. In this method, apparent recovery of applied N fertilizer is estimated by subtracting the N recovery by plants grown on unfertilized control plots from that by plants grown on fertilized plots. Hauck (1971) reported that percent uptake of applied N is generally overestimated using the difference method, when compared with the ^{15}N tracer method. This is because the

addition of N fertilizer to the soil induces mineralization of soil organic matter. This is often referred to as the "priming effect". When mineralization occurs, N is released and taken up by the plant. The difference method estimation of N-uptake does not differentiate between these two sources of N resulting in an overestimation of fertilizer recovery. Low and Piper (1957) calculated N recovery using the difference method and the ^{15}N tracer method. They found that N uptake calculated by the difference method was greater than the amount calculated by the ^{15}N tracer method. This suggests that plants took up more soil N where fertilizer was applied. Terman and Brown (1968) compared the difference method with another recovery method. They indicated that the difference method is over-simplified and does not effectively characterize the efficiency of applied N. However, due to the high cost of isotope tracer methods in large-scale field experiments, the difference method should be considered as a part of any N recovery study, and results compared with other methods.

^{15}N Tracer Method

Tracer methods allow direct N measurement in N transformations, N uptake by the plant, and fertilizer studies. Without such techniques, N can only be studied indirectly. Thus, many advantages can be derived from using tracer techniques. ^{15}N is often used as tracer in the studying of the N cycle and its inherent processes. The stable isotope ^{15}N is used because it occurs naturally in combination with ^{14}N in an

almost constant ratio of 0.3663 atom % ^{15}N (Naude, 1930). Likewise the chemical properties of ^{14}N and ^{15}N are generally identical, making ^{15}N ideal for the study of N.

However, there are three assumptions which must be made when conducting research using tracer methods. According to Hauck and Bremner (1976) these assumptions are: 1) elements containing two or more isotopes (complex elements) have a constant isotope composition in the natural state; 2) one isotope from the same element cannot be distinguished from another by living systems; and 3) biochemical systems maintain the chemical identity of the isotopes. These assumptions are not valid in every experimental situation. However, they are valid for most tracer studies.

The non-radioactivity of ^{15}N makes this isotope ideal as a research tool for many reasons. First, the use of ^{15}N imposes no time limitation since there is no isotopic decay (Nason and Myrold, 1991). Furthermore, the use of ^{15}N does not cause any ill effects from radiation poisoning, either to the experimenter or the system under study. Finally, there is no disposal problem associated with ^{15}N residues and no permits are required for its use.

The ^{15}N tracer method offers several advantages over non-tracer methods for research on N. According to Hauck and Bremner (1976) these advantages include: 1) positive identification of the labeled N as it enters and moves through an ecosystem; 2) no control treatments are required; and 3)

pre-sampling of the investigation site is not required. There are disadvantages to using the ^{15}N tracer method as well. The largest obstacle to overcome is the initial cost and the cost of equipment needed for ^{15}N analysis. However, as ^{15}N has become widely used as a research technique, these limitations have diminished.

^{15}N has been useful in following the complex inter-relationships between organic and inorganic N. Many researchers have used ^{15}N isotopes in experiments concerning N uptake and transformation in the soil, water and plant system. Research using ^{15}N to measure the dynamics of N cycling can be divided into three categories: 1) use of ^{15}N as a tracer, 2) isotope dilution experiments, and 3) the application of mathematical models to ^{15}N dynamics (Myrold and Tiedje, 1986).

Tracer studies have been used to determine the fate and partitioning of applied ^{15}N . However, tracer studies can only provide a qualitative estimate of process rates. Isotope dilution experiments involve the addition of ^{15}N into a product pool. Dilution of the atom % ^{15}N in this pool by natural abundance N from a precursor pool is investigated over time. These studies have been used to investigate selected N cycle rates in sediments and soils. (Koike and Hattori, 1978; Nishio et al., 1985) The use of ^{15}N to characterize total pool sizes in mathematical N cycle models was first begun by Kirkham and Bartholomew (1955). The application of mathematical models to N cycling in soils allows rates of several N-cycle processes

to be estimated simultaneously. All of these methods using ^{15}N provide the researcher with valuable information.

Walker et al. (1956) determined the fate of $^{15}\text{NH}_4^+$ and $^{15}\text{NO}_3^-$ applied to pots in which grass, clover, and grass plus clover were grown. Approximately 30% of the applied N was lost through denitrification. The researchers concluded that uptake of soil N by the plant was increased by the application of N fertilizer. This was evidence of the immobilization of ^{15}N by soil organisms as well as the biological interchange of ^{15}N for soil N.

Tyler and Broadbent (1958) investigated uptake of applied ^{15}N . They indicated that much of the applied ^{15}N was immobilized soon after it was applied. Legg and Allison (1959) applied ^{15}N to sudangrass (Sorghum sudanense Piper). They recovered an average of 93.6% of the ^{15}N applied in this study.

Cady and Bartholomew (1960) also conducted a greenhouse study to investigate the uptake and recovery of ^{15}N applied to sudangrass. They found that the addition of an organic amendment decreased the percent of ^{15}N recovered in the grass.

Dilz and Woldendorp (1961) studied the distribution of N in plant and soil using ^{15}N KNO_3 applied to grass. They found that differing levels of moisture had no effect on N distribution in sandy and clay soils. However, there was an effect on N recovery in peat soils. The recovery rate of ^{15}N in peat soils was much less than that from clay or sand.

Allison (1964) found that recovery rates for ^{15}N studies

conducted in a greenhouse were higher than recovery rates for lysimeter and field experiments. The recovery rates of applied ^{15}N in greenhouse studies averaged 86%. Much of the research suggested most of the unaccounted-for N was lost due to denitrification. Most field experiments reviewed by Allison showed considerably lower recovery rates.

Carter et al. (1967) conducted a field study in which the recovery rates of applied N fertilizer were investigated. Cylinders were driven into the soil and sudangrass was grown on top. Total recovery of the applied ^{15}N averaged 99%, and no significant differences in recovery rates were found to be caused by treatment, cropping, or time of application.

Westerman et al. (1972) conducted a field experiment to investigate the recovery of N from urea and oxamide ^{15}N using a sorghum-sudan hybrid. The crop was harvested four times during the experiment. Urea ^{15}N evidenced a 51% recovery rate by the plant with 28% left in the soil (0 to 25cm). Oxamide ^{15}N evidenced a recovery rate of 52% by the plant with 31% left in the soil (0 to 25cm).

Edwards and Hauck (1974) conducted a greenhouse pot experiment using both ^{15}N -depleted and ^{15}N -enriched material. Fertilizer particles were prepared from $(\text{NH}_4)_2\text{SO}_4$ with a depleted value of 0.031 atom % ^{15}N and an enriched value of 0.734 atom %. These two treatments were then compared by measuring plant uptake of the applied ^{15}N forms. They found

no difference in N recovery rates for five harvests taken over an 18 week period at three rates of application.

Dowdell and Webster (1980) conducted a monolith lysimeter study to investigate the uptake of ^{15}N fertilizer by perennial ryegrass swards and losses by leaching. Forty three to 54% of the ^{15}N fertilizer applied was recovered, with between 4.6 and 9.5 % of the original applied ^{15}N being taken up in the following year and 1% being taken up in the fifth year of the experiment.

Kowalenko (1980) used ^{15}N on Manotick sand to determine the transport and transformations of N fertilizer in a sandy field plot. He found that leaching, denitrification, clay fixation of NH_4^+ , mineralization and immobilization each played a significant role in the transport and transformation of applied N.

Strebel et al. (1980) used ^{15}N to determine nitrate and water uptake by spring wheat. The study was conducted on a Udalf formed from loess, with uptake as a function of soil depth and time being determined. Data were collected to compute total vertical water flow, capillary water flow, water flow through the roots, labeled fertilizer recovery, total nitrate content in the soil, and mass flow of nitrate to plant roots. These values were then compared with N uptake by the plant through different growth stages. They found that 76% of the total N uptake was by mass flow and that 62% of the total water uptake came from the arable layer (0-30 cm). Because of

the high water uptake rates and high $\text{NO}_3\text{-N}$ concentrations in the Ap horizon, this layer contributed most to the supply of $\text{NO}_3\text{-N}$.

Power and Legg (1984) conducted a field lysimeter study utilizing ^{15}N to investigate the fate of N fertilizer applied to grasslands. During this course of the experiment, soil, grass and root samples were collected for analysis. Highly variable precipitation and evapotranspiration rates contributed to a five-fold variation in annual top growth. From 12 to 52% of the ^{15}N applied was recovered in top growth during the initial season, representing about 75% of the total isotope recovery in tops after four additional growing seasons. The roots contained approximately 15% of the applied ^{15}N after the initial growing season, with approximately two thirds of this N appearing in plant tops within three years. ^{15}N content of the soil varied from 29 to 49% of the fertilizer applied, present mostly as organic N after the first season. Power and Legg recovered between 70 and 95% of the ^{15}N applied in the tops, roots, and soil during the five years of the experiment.

Nishio et al. (1985) conducted an experiment in aerobic soil which simultaneously determined the rates of mineralization, immobilization, and oxidation of N in the presence and absence of acetylene using a $^{15}\text{NH}_4^+$ dilution technique. The acetylene inhibited nitrification but did not directly affect mineralization and immobilization. They reported that denitrification or immobilization of nitrate was negligible.

Mineralization proceeded much faster than immobilization with net mineralization accounting for 22 to 59% of the gross mineralization. Nitrogen transformation rates were higher at a soil moisture content of 60% than at 40%. They concluded that, in soil, the pool size of nitrogenous compounds is controlled by several microbial reactions which occur simultaneously. The combined use of the $^{15}\text{NH}_4^+$ dilution technique, coupled with kinetic model analysis, provided a novel approach for understanding the dynamics of N transformations.

Impithuska and Blue (1985) conducted a field study using enriched $^{15}\text{NH}_4^{15}\text{NO}_3$ to investigate N absorption by three warm-season grasses grown on a Florida Spodosol. Recovery rates in the forages for the average of the two N rates and three ^{15}N applications were: 35% of that applied to Ona stargrass, with 13% present in the stolon and root mass and 22% present in the soil; 40% of that applied to Transvala digitgrass with 9% of that present in the stolon and root mass and 17% present in the soil; and 35% of that applied to Pensacola Bahiagrass, with 20% of that present in the stolon and root mass and 20% present in the soil. Results from the study indicated: 1) essentially equal quantities of ^{15}N in the three warm-season grasses; 2) large retention of ^{15}N in these sandy soils; and 3) a large amount of non-fertilizer N in the forages during 1977, the year of ^{15}N application.

Varvel and Peterson (1991) conducted a study using ^{15}N to investigate N fertilizer recovery and use by grain sorghum

in monoculture and rotational systems. Grain sorghum was grown under rain-fed conditions on a silty clay loam. Broadcast applications of depleted $^{15}\text{NH}_4\text{NO}_3$ were made at 90 and 180 kg N ha⁻¹ in 1985 and 1986. Recovery rate as determined by the isotopic method was higher than for grain sorghum in monoculture at 65% than grain sorghum in rotation at 55%. Fertilizer N recovery rates determined by the difference method ranged from 119% in continuous grain sorghum to 9% in sorghum following oat plus clover. Recovery rates differed for the isotopic and difference methods, which suggests that N fertilizer applied to grain sorghum in various cropping systems was entering different organic soil-N pools.

Nitrogen tracer methods appear to be indispensable in the study of the fate of N in turfgrass ecosystems. For many nutrient cycling and management studies, using the ^{15}N tracer method enables one to better understand and quantify the N present in the turfgrass systems over extended time periods.

CHAPTER 3
NITROGEN RELEASE RATES OF REACTIVE-LAYER COATED
UREA, AMMONIUM SULFATE, AND POTASSIUM NITRATE

Introduction

Nitrogen fertilizer use efficiency by the plant is affected by soil, plant, and environmental conditions. Increasing N uptake efficiency is an environmental and economic necessity. As a result of processes such as leaching volatilization, immobilization, and denitrification, the N fertilizer effect often diminishes quickly. Application of N fertilizers, therefore requires relatively large dosages which may be expensive and may cause environmental pollution. Coating technologies have provided viable alternatives to other synthetic organic and inorganic N sources through the use of controlled-release fertilizers (CRFs) which are more efficient and less costly.

Controlled-release fertilizers provide an extended supply of nutrients through the gradual release of the substrate which they enclose. The controlled-release characteristic minimizes losses of N to the environment and increases uptake efficiency by the plant. Depending on the coating technology used, release rates will vary with coating thickness and membrane material. Recent advances in fertilizer coating technology have developed a new process which improves the

release rate as well as lowering the cost of the coated product, through the use of an ultra-thin coating. This new process is referred to as Reactive-Layer Coating (RLC) (Moore, 1987).

The RLC process involves placing fertilizer granules in a drum rotating at 10 rpm and heated to 90°C (Figure 3-1). A twin nozzle setup consisting of two separate pneumatic spraying nozzles, is positioned in the drum approximately 5 cm from the substrate of rolling granules. From one nozzle a thin layer of diphenylmethane diisocyanate is sprayed on the fertilizer. This reacts with the NH_2 groups of the urea, forming a reactive layer coating and leaving excess unreacted NCO groups. (It is unknown how diphenylmethane diisocyanate reacts with $(\text{NH}_4)_2\text{SO}_4$ and KNO_3) Hot (100°C) aromatic polyester polyol is sprayed from the second nozzle on the product, reacting with the free NCO groups to form a water-insoluble sealing layer which allows water vapor to enter the granule through diffusion. The thickness of the coating layer is built up by the simultaneous spray from both nozzles.

The objectives of this study were to determine the effects of temperature, coating thickness, substrate and granular size on RLC urea (CUrea), ammonium sulfate (CAS), and potassium nitrate (CKNO_3) release rates.

Materials and Methods

A laboratory study was conducted using RLC urea, AS, and KNO_3 with different coating thicknesses and granule sizes

(Table 3-1). Duplicate five gram samples of each fertilizer material were placed in plastic containers containing 50 ml of deionized water. The plastic containers were maintained at 25°C and 35°C for 63 days. Containers were shaken prior to sampling in order to homogenize the released N within the solution. solutions were sampled on the 3rd and 7th days, and then weekly for the remaining experimental period. All samples were analyzed for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ using an air segmented Rapid Flow Analyzer (RFA) unit. The RLC urea materials were also analyzed for urea-N using a colorimetric

Table 3-1. Fertilizer material specifications.

Fertilizer	% Coating Weight	Particle Size (U.S. Std. sieve)
CAS	4.7	-6+10 (macro)
CAS	9.8	-6+10
CAS	7.5	-14+30 (micro)
CAS	15	-14+30
CUrea	4.8	-6+10 (macro)
CUrea	10	-6+10
CUrea	10.5	-14+30 (micro)
CUrea	21	-14+30
CKNO ₃	3	-10+14 (micro)
CKNO ₃	6	-10+14

method (Bremner, 1982). At termination of the study, all fertilizer materials were dried and weighed for gravimetric determination of substrate release. Statistical analysis of data was performed using Statistical Analysis System (SAS)

procedures. The least significant difference (LSD) method was used for means separation.

Results and Discussion

The release rate of encapsulated controlled-release N fertilizers is affected by several factors. These include temperature, moisture, chemical, biological and photo degradation of the coating, coating thickness, nature of the coating, fertilizer particle size, and distribution density, along with, the (temperature dependent) solubility of the N substrate that is being released. The impact of these factors on N release rates can be controlled through the selection of a coating type and thickness that will be most effective for the environment in which it will be applied. Reactive-layer coated materials investigated in this study showed that the rate of N release is affected by temperature, coating thickness, size, and N substrate.

Effect of Temperature

Temperature effects on release rates of N from the RLC materials investigated were evident by comparing N release at 25°C and 35°C (Figure 3-2). Increasing temperature increases the rate of diffusion of water vapor, as well as the solubility of the substrate resulting in an increase in the rate of N release. Hauck (1972) suggested that the first phase of nutrient release from coated fertilizers is the diffusion of water vapor from the surrounding environment through the coating into the granule. The second phase, after the

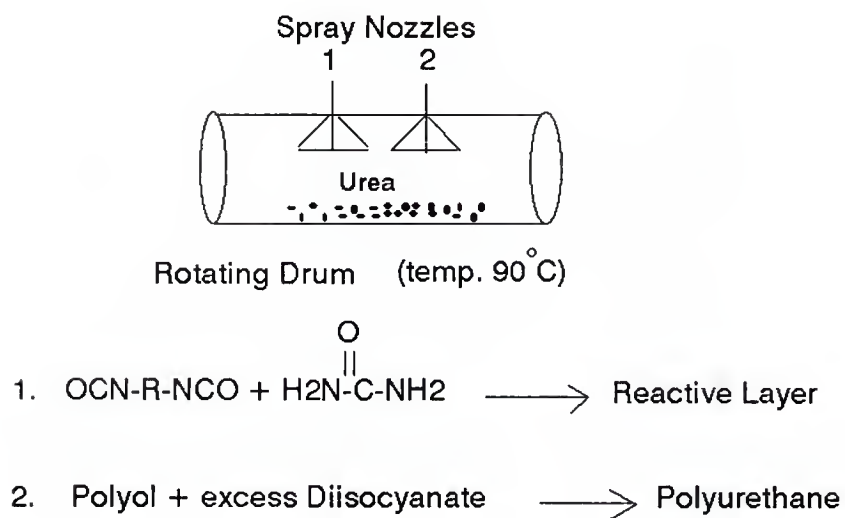
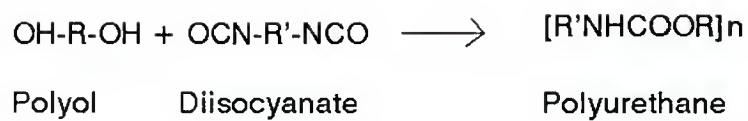


Figure 3-1. Reactive-layer coating process.

condensation of water inside the granule and the buildup of hydrostatic pressure, is the outward flow of concentrated fertilizer solution. Thus, temperature and solubility of the N substrate are the determining factors in the release rate of N from the fertilizer granule.

The increase in temperature from 25°C to 35°C increased release from 30% to 56% for CAS-4.7. The release rate from CAS-9.8 was doubled as well, but only from 3% to 6% as a result of increasing temperature. Release rates from C Urea-4.8 and C Urea-10 increased from 70% to 78% and from 38% to 51%, respectively. Christianson (1988), studied the effect of temperature on the release rate of urea from RLCU (7.6% coating weight) in a 5-week incubation study with temperatures ranging from 9 °C to 30 °C. He found that when temperature increased from 9 °C to 30 °C, the release rate of urea increased from 17% to 72%, respectively.

The difference in release rates between these two substrates can be attributed to differences in their solubility characteristics. The solubility of ammonium sulfate is lower than that of urea at the temperatures over which this experiment was conducted. Therefore, increasing temperature had a more profound affect on the solubility of AS than on urea, resulting in a larger increase in the release rate of N.

The increase in temperature, increased percent N release from the micro-size materials as well. However, the increase

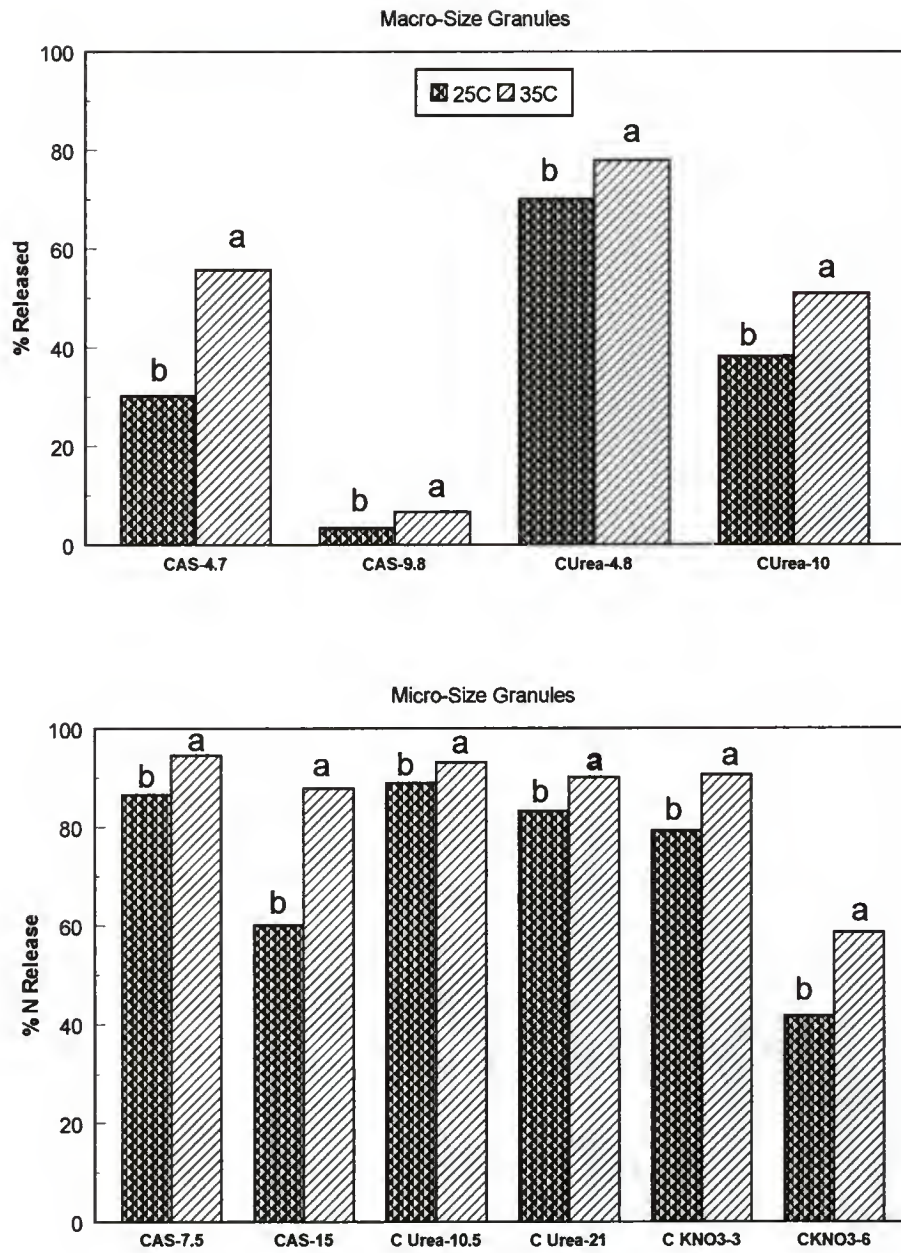


Figure 3-2. Effect of temperature on % N released.

was smaller in magnitude compared to the macro-size materials, with the exception of CAS-15 and CKNO3-6. These exceptions were most likely the result of a combination of the low solubility and high coating thickness on these two substrates compared to urea. In general, the percent release from the micro-size materials was higher than for their macro-size counterparts, even though the percent coating weight for the micro-size materials was generally higher. This is a result of the smaller particle size of these materials which, increases surface area and subsequently increases percent release.

Effect of Coating Thickness

Increasing coating thickness resulted in extended diffusion time and therefore, slower release rates and less N released during the 63-day experimental period (Figures 3-3 through 3-7). In general, increasing coating thickness resulted in a slower rate of release of N from the capsules, with the exception of the urea materials. As a result of the slower release rates, the more thickly coated materials released less N overall. However, although N release for both coating thicknesses increased at the higher temperature, the heavily coated materials had a higher rate of increase in N release. This resulted in a smaller difference in overall N release between the two coating thicknesses during the latter part of the experimental period at the higher temperature.

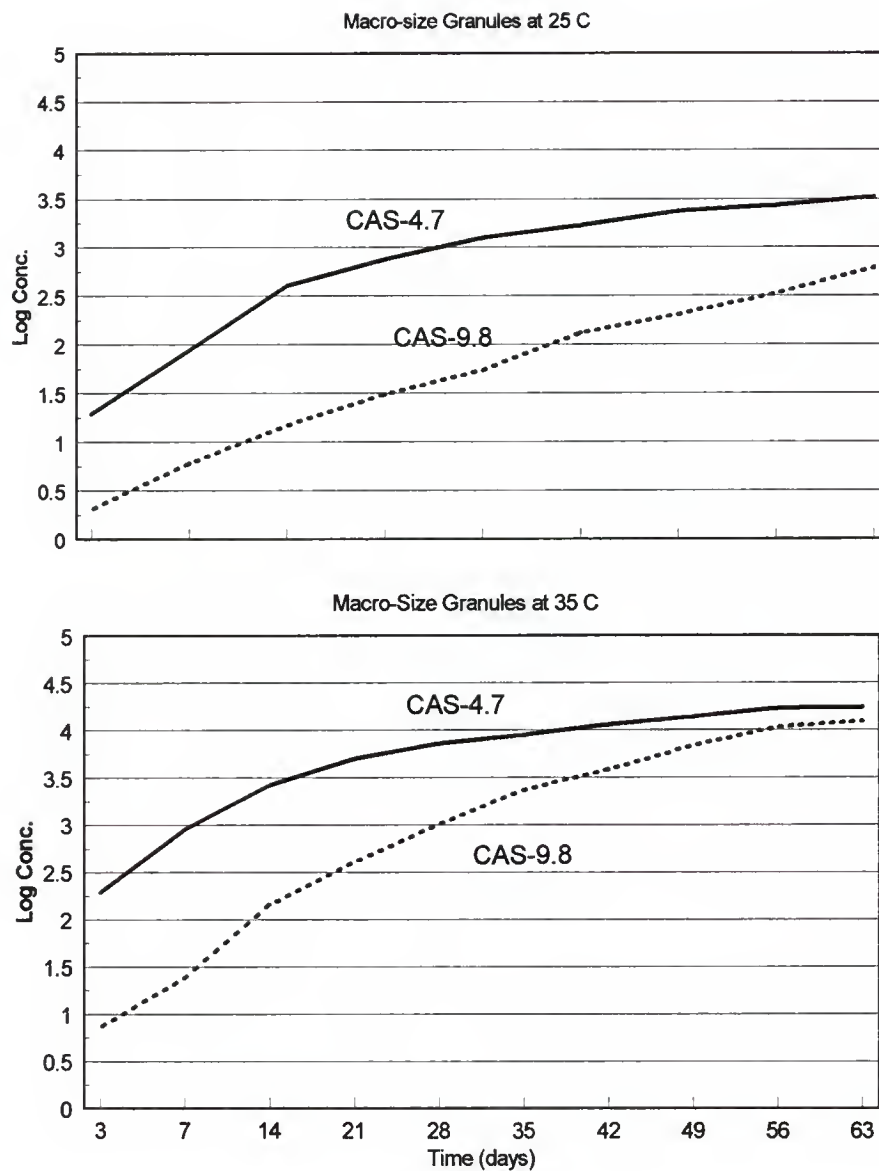


Figure 3-3. Effect of coating thickness and temperature on N release from CAS: macro-size.

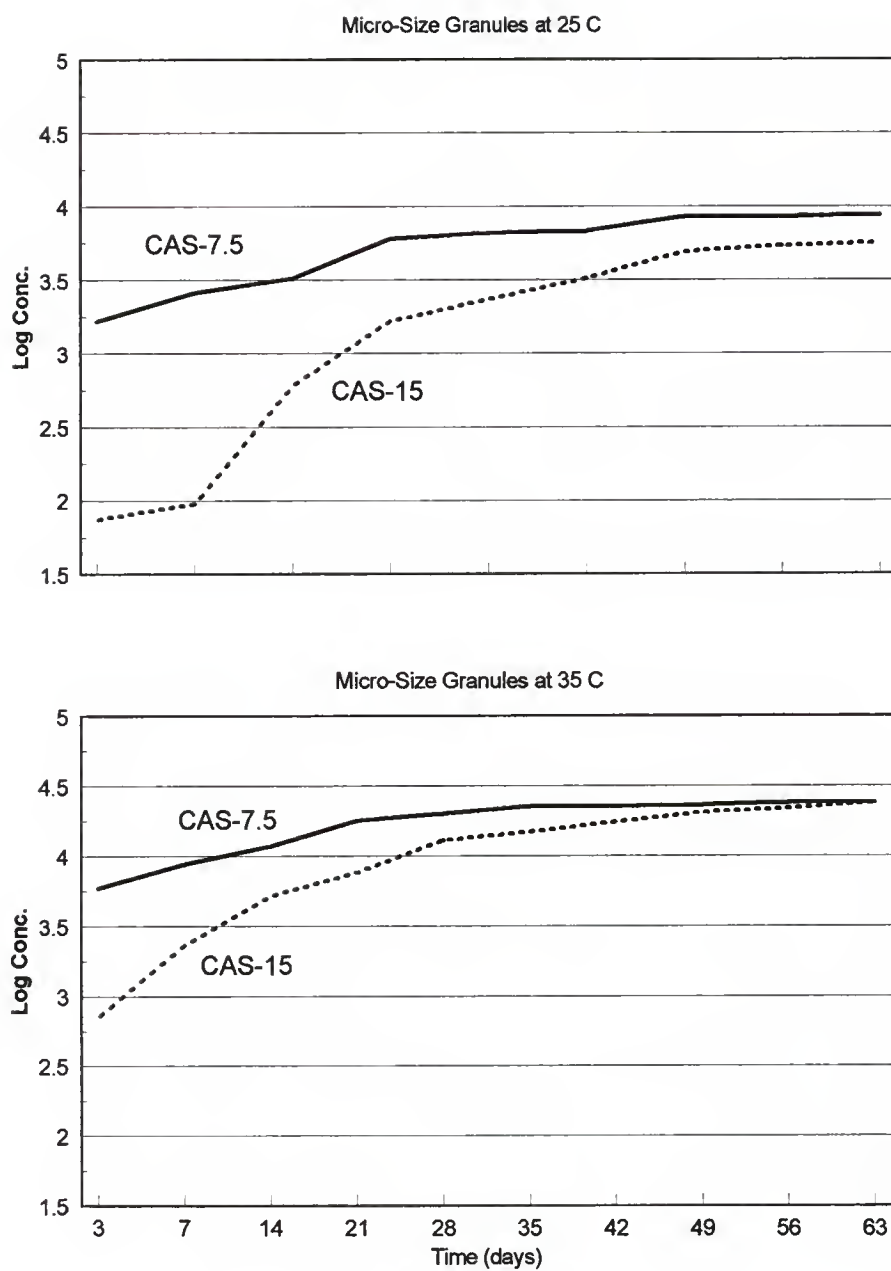


Figure 3-4. Effect of coating thickness and temperature on N release from CAS: micro-size.

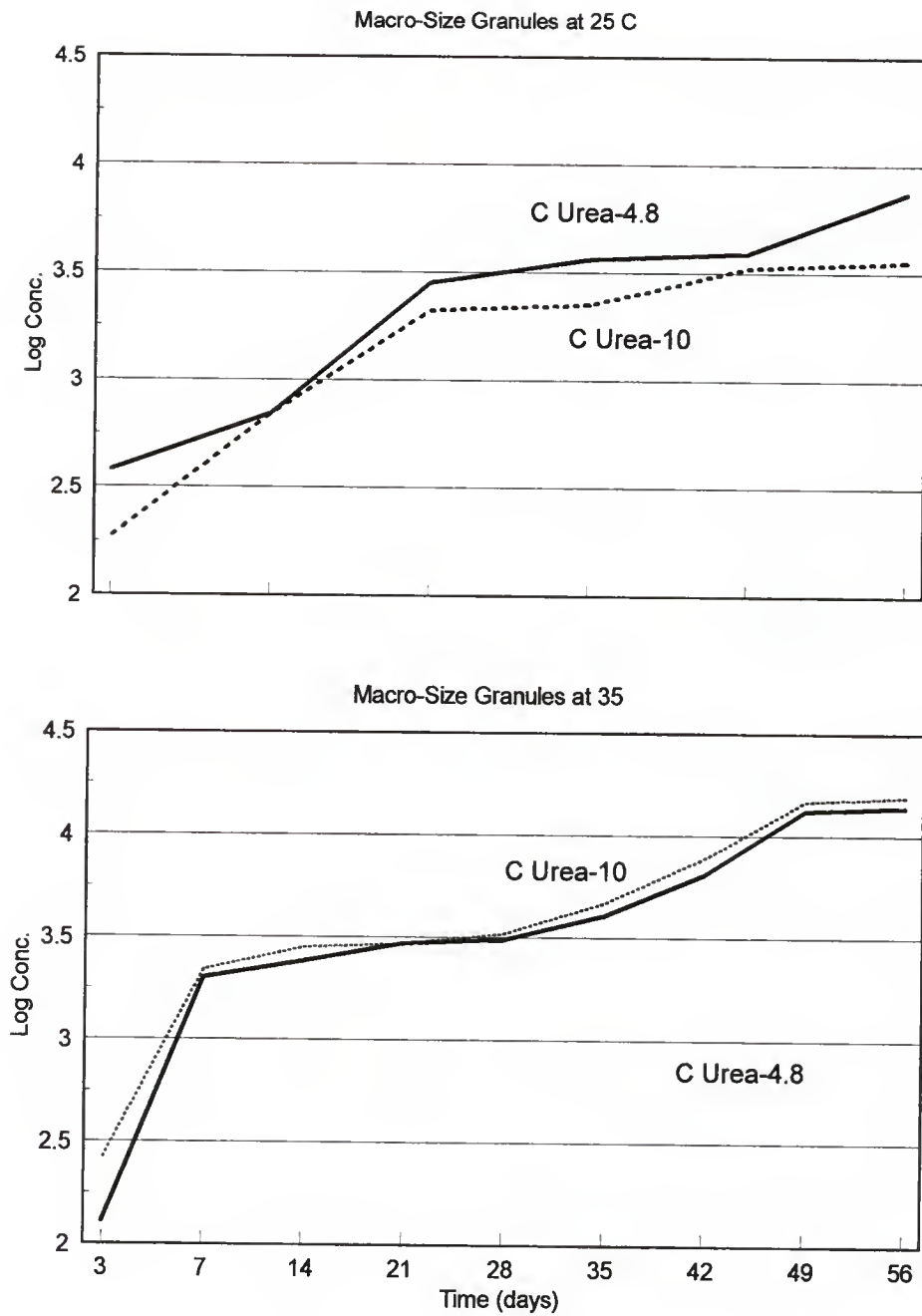


Figure 3-5. Effect of coating thickness and temperature on N release from C Urea: macro-size.

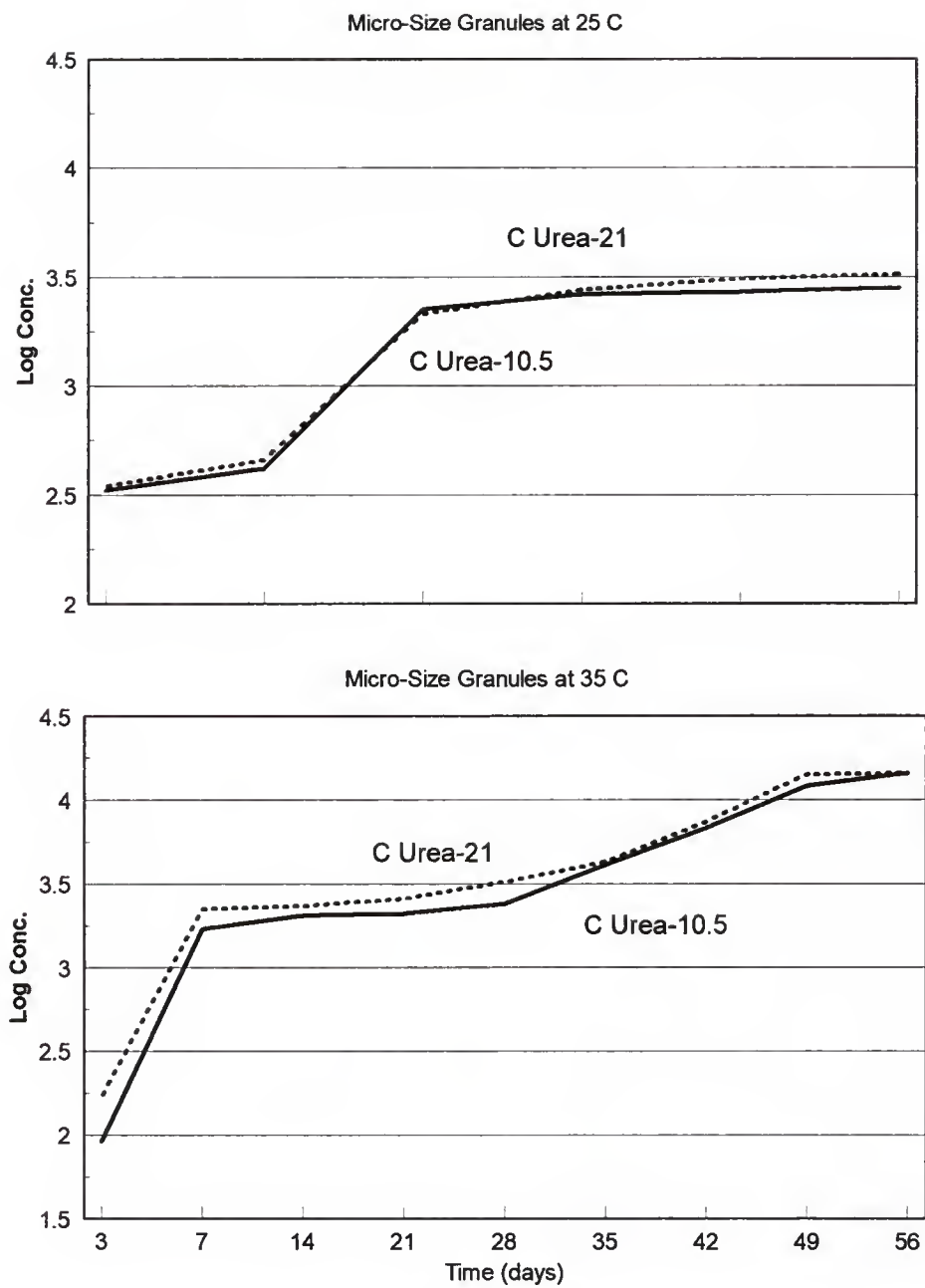


Figure 3-6. Effect of coating thickness and temperature on N release from C Urea: micro-size.

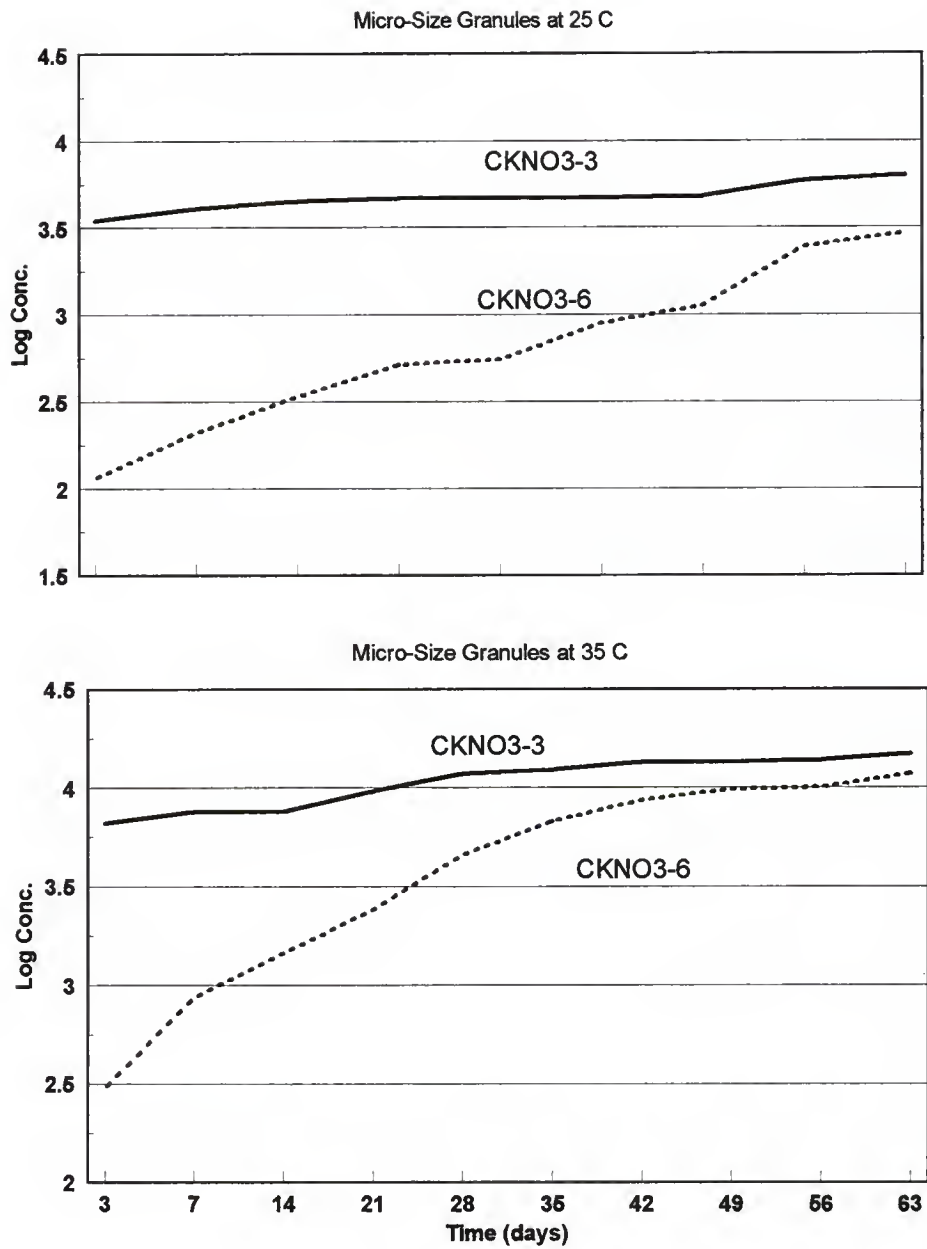


Figure 3-7. Effect of coating thickness and temperature on N release from CKNO₃: micro-size.

Coated KNO_3 -3 did not exhibit the slow-release characteristics that the other coated materials exhibited. Nitrogen release was essentially complete by the end of the first week of the experiment. This suggests that the 3% coating weight was not sufficient to regulate N release. However, increasing the coating on KNO_3 from 3% to 6% had a profound effect on release rates. The total N released from CKNO_3 -6 at 25°C was the lowest compared to all other micro-size treatments.

A coating effect was also observed among the urea materials for overall N release (Figure 3-2). However, the release patterns did not seem to reflect these differences (Figure 3-6). This may have been the result of NH_3 volatilization from the urea materials, as was suggested by the high pH (9 to 10) of the solution sampled.

In general, the N release patterns observed were indicative of the two stage release process described by Christianson (1988). During the first phase of N release, release rate is regulated by the rate of the dissolution of the N substrate within the granule and its subsequent movement through the coating wall. When dissolution of the N substrate is complete, the rate of diffusion begins to decrease as the concentration of N decreases inside the granule during the second stage of N release. This explains the non-linear shapes of the N release curves shown in Figures 3-3 through 3-7.

Effect of N Substrate

Nitrogen substrates used in this study affected both the release rates and the quantities released. This is primarily the result of differences in their solubilities. In order for a substrate to diffuse through the coating membrane, it must first enter into solution, so solubility has a higher effect on the rate and quantity at which a substrate enters solution. Urea was the most soluble N substrate used. It reaches 100% solubility (w/v) at 17°C (Perry and Chilton, 1973). Ammonium sulfate has a solubility of 75% at 20°C. However, as temperature increases the solubility of ammonium sulfate increases to 78% at 30°C and 81% at 40°C. Potassium nitrate, on the other hand, has a solubility of 32% at 20°C, increasing to 46% and to 64% at temperatures of 30°C and 40°C, respectively. Therefore, temperature and subsequently the solubility of the different N substrates, influenced the rate and quantity of N released. High solubility of urea (100% at 17°C) suggests that varying temperature did not affect the solubility of urea as it did ammonium sulfate and potassium nitrate.

The reaction of these three N substrates with the coating may have also influenced the conductivity of the membrane and therefore the release rates of the N. Moore (1987) showed that the polymer used in reactive-layer coatings chemically reacts with -NH_2 groups of urea and forms a reactive layer which affects the kinetics of the release. However, no information is available which suggests that the same reaction

occurs with inorganic N substrates such as ammonium sulfate and potassium nitrate. The data suggest that the reaction which takes place when urea is coated may have played a role in increasing the release of urea in addition to its solubility. However, coating thickness is the primary factor regulating the rate of N release.

Summary and Conclusions

Reactive-layer coated N fertilizers showed different N release rates and subsequent total amount of N released. Factors affecting these differences were temperature, coating thickness, particle size and N substrate. A 10°C increase in temperature increased total N released, ranging from 8% to 50% for the macro-size materials and from 3% to 28% for the micro-size materials. The ranges in N release were affected by coating thickness and N substrate, with increasing coating thickness decreasing the total percent of N released in all cases. However, the magnitude of the decrease depended on the N substrate.

This study demonstrated that the release of N can be optimized through the manipulation and consideration of different factors. Consideration of environmental factors such as temperature (climate and season) and selection of different coating thicknesses could optimize N release and subsequent use efficiency by the plant, and minimize losses to the environment.

CHAPTER 4
THE EFFECT OF REACTIVE-LAYER COATED
UREA AND AMMONIUM SULFATE ON GROWTH AND
N UPTAKE OF BERMUDAGRASS

Introduction

The turfgrass industry in the United States is a multi-billion dollar per year industry. Turfgrass use includes residential lawns, golf courses, parks and sports facilities, roadways, and educational and research facilities. Nitrogen is the primary nutrient required for turfgrass production and maintenance. This translates into several million tons of N applied to turfgrass annually.

Golf courses alone account for more than 1.3 million acres of managed turfgrass in the United States (Cohen et al., 1993), requiring approximately 300,000 tons of N annually. Therefore, the efficient use of N is essential for both economic and environmental reasons.

Controlled-release N fertilizers are used as a management tool to prolong N availability to turfgrass and to increase the use efficiency of the applied N. The objectives of the following two studies were to investigate the growth, N uptake, and quality response of bermudagrass to reactive-layer coated ammonium sulfate and urea with varying coating thicknesses.

Experiment 1: 1992

Materials and Methods

This field study was conducted on established Tifway bermudagrass at the G.C. Horn Turfgrass Field Laboratory in Gainesville Florida between June and September, 1992. Treatments (Table 4-1) were arranged in a randomized complete block design and replicated three times.

Table 4-1. Nitrogen treatment specifications (1992).

Treatment	N Substrate	% Coating
$(\text{NH}_4)_2\text{SO}_4$ (AS)	$(\text{NH}_4)_2\text{SO}_4$	0
Coated AS (CAS-4.7)		4.7
Coated AS (CAS-9.8)		9.8
Urea	UREA	0
Coated Urea (CUrea-4.8)		4.8
Coated Urea (CUrea-10)		10

Each treatment was applied to a 2 x 3 meter turf plot maintained at a 2 cm mowing height. Treatments were applied at 1.5 Kg N 100 m⁻². All plots received phosphorus and potassium at a rate of 0.5 and 0.25 Kg 100 m⁻², respectively. Plots receiving urea treatments also received sulfur in the form of calcium sulfate in order to balance the sulfur present in the AS treatments applied to other plots. Grass was mowed at a height of 2 cm and all clippings were collected on a weekly

basis, for a total of 15 harvests during the 104-day experiment. Clippings were weighed for growth rates and digested for total Kjeldahl nitrogen (TKN) analysis (Bremner and Mulvaney, 1982), using an air segmented Rapid Flow Analyzer (RFA). Visual quality ratings were taken biweekly for turfgrass quality and evaluations. Statistical analysis of data was performed using Statistical Analysis System (SAS) procedures. The least significant difference (LSD) method was used for means separation.

Results and Discussion

Growth of Bermudagrass

Bermudagrass growth was affected by several factors throughout the experimental period including the available N pool, temperature, daylight, and rainfall. However, N substrate and coating thickness had the most profound effects on growth rates. Growth responses over the 104-day experiment are presented in Table 4-2.

Coated Urea-10 produced the highest total bermudagrass growth, followed by CAS-4.7 and C Urea-4.8. Plots receiving uncoated urea and ammonium sulfate produced similar overall growth and an identical growth pattern. Bermudagrass growth was lowest in response to CAS-9.8, because the release rate of N was insufficient to sustain growth. Bermudagrass growth and N release from coated fertilizers were highest during the month of July for all treatments, because of optimum daylight, temperature and increased rainfall.

Ammonium sulfate treatments. Growth of bermudagrass during the first 32 days was not influenced by coating ammonium sulfate (AS). During this 32 day period, coated ammonium sulfate (CAS) with 4.7% and 9.8% coating produced 27% and 28% of total bermudagrass growth, respectively, for the 104 day experiment. However, the bermudagrass growth in response to uncoated ammonium sulfate (AS) during the 32 period was 36% of total growth. Cumulative growth of bermudagrass at 65 days for the CAS-9.8 treatment was lower than the other two AS treatments. The CAS-9.8 treatment had a slower N release rate than the other two AS treatments (Chapter 3).

Table 4-2. Cumulative growth of bermudagrass following N application (g plot⁻¹).

Treatment	Days After Application		
	32	65	104
AS	501a*	1080a	1381b
CAS-4.7	507a	1303a	1848a
CAS-9.8	322a	726b	1153b
CV**	24	17	14
Urea	509a	1118a	1435b
CUrea-4.8	605a	1307a	1718ab
CUrea-10	569a	1373a	1876a
CV	20	15	13

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅;

**Coefficient of variation (%).

The percent of total growth at 65 days differed according to fertilizer coating thickness. The CAS-9.8 treatment produced 63% of total bermudagrass growth during the 65 day period, whereas CAS-4.7 produced 71% of the total growth during this same period. However, AS produced 78% of the total growth during this time. This suggests a faster rate of depletion for this uncoated substrate.

Bermudagrass growth slowed in the latter part of the experiment in response to the uncoated AS treatment, apparently because of depletion of the N source. Total growth of bermudagrass in response to uncoated AS was 1381 g plot⁻¹. Overall growth of bermudagrass in response to CAS-4.7 was highest (1848 g plot⁻¹) at 104 days after N application and lowest for CAS-9.8 (1153 g plot⁻¹).

The growth data indicate that coating AS increases total growth of bermudagrass over extended periods of time. However, if the coating is too thick, the N will fail to release rapidly enough and growth could be even lower in response to a heavily coated material than the uncoated material. Peacock and DiPaola (1992) found a similar result in their study comparing the effect of coated urea treatments with varying coating thicknesses on bermudagrass growth. The thickly coated urea treatment (12.5%) produced a significantly lower growth when compared to growth produced by the more thinly coated urea treatments and uncoated urea.

Urea treatments. The growth of bermudagrass during the first 32 days exhibited no differences to the coating of urea. During this period, coated urea (C Urea) with 4.8% and 10% coating and uncoated urea produced 30%, 35% and 35% of total growth of bermudagrass, respectively, for the 104 day experiment. Cumulative growth of bermudagrass at 65 days still showed no differences in response to the different coating thicknesses, with the percentages of total growth equalling 73% in response to C Urea-10, 76% in response to C Urea-4.8, and 78% in response to uncoated urea. By the 87th day of the experiment, however differences in growth were detected between C Urea-10 and uncoated urea. These differences persisted throughout the remainder of the 104 day experiment.

The growth data demonstrate that coating urea increased bermudagrass growth over time. Total bermudagrass growth was highest in response to C Urea-10 (1876 g plot⁻¹) followed by C Urea-4.8 (1718 g plot⁻¹) and then uncoated urea (1435 g plot⁻¹). Although bermudagrass growth in response to uncoated urea was similar initially, growth dropped off as the applied N source was depleted. This data is consistent with the findings of Mikkelsen et al. (1994) in a study they conducted comparing coated and uncoated N sources. They found that the coated materials were more effective in increasing yields of stems and leaves than uncoated materials because these materials were better able to release nutrients in synchrony with plant demand.

Nitrogen Uptake

Bermudagrass N uptake pattern in response to the treatments was similar to that of growth (Table 4-3). Nitrogen substrate and coating thickness of applied N fertilizers affected total N uptake by the bermudagrass during the 104 day experiment.

Ammonium sulfate treatments. Bermudagrass N uptake during the first 32 days was not affected by differences in coating thickness among the ammonium sulfate treatments. During this 32 day period, coated ammonium sulfate (CAS) with 4.7% and 9.8% coating resulted in 30% and 26% of total N uptake by bermudagrass, respectively, for the 104 day

Table 4-3. Cumulative N uptake by bermudagrass following N application (g plot⁻¹).

Treatment	Days After Application		
	32	65	104
AS	16.68a*	35.34ab	44.82b
CAS-4.7	18.62a	46.45a	63.81a
CAS-9.8	9.85b	21.69b	37.63b
CV**	35	20	16
Urea	17.96a	39.30a	49.18b
CUrea-4.8	22.16a	48.03a	61.06ab
CUrea-10	19.74a	50.79a	67.87a
CV	23	15	13

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅;

**Coefficient of variation (%).

experiment. However, the N uptake by the bermudagrass during the 32 day period in response to uncoated ammonium sulfate (AS) was 38% of total N uptake. Cumulative N uptake by bermudagrass at 65 days showed a difference between CAS-9.8 and the other two AS treatments. The CAS-9.8 treatment did not have an N release rate that was sufficient to produce an N uptake similar to that of the other two AS treatments during this 65 day period. There was no difference in N uptake between AS and CAS-4.7.

The percent of total N uptake at 65 days differed according to coating thickness of the fertilizer. The CAS-9.8 treatment resulted in an N uptake of 22 g N plot⁻¹ by the bermudagrass. This represents 58% of the total N uptake by bermudagrass during the 104 day experimental period. Cumulative N uptake of bermudagrass at 65 days for plots receiving CAS-4.7 was 46 g N plot⁻¹, or 73% of the total N uptake over the 104 day experimental period. However, application of uncoated AS resulted in an N uptake of 35 g N plot⁻¹. This represents 79% of the N uptake during entire the experimental period for this treatment.

At the end of the 104 day experimental period, differences in N uptake were observed among the ammonium sulfate treatments. Nitrogen uptake by bermudagrass in response to uncoated AS slowed in the latter part of the experiment, as a result of depletion of the applied N source. Total N uptake by bermudagrass was highest in response to CAS-4.7 (64 g N

plot⁻¹) at 104 days after N application, and lowest for CAS-9.8 (38 g N plot⁻¹). Total N uptake by bermudagrass was 45 g N plot⁻¹ in response to uncoated AS.

The N uptake data showed that coating ammonium sulfate with a 4.7% coating increases total N uptake by bermudagrass over extended periods of time. However, increasing the coating to 9.8% resulted in a substantial decrease in overall N uptake compared to CAS-4.7. Nitrogen uptake patterns revealed that, after 65 days, N uptake by bermudagrass in response to uncoated AS slowed because of the depletion of uncoated AS due to high N uptake during the first 65 days and higher losses of this uncoated N compared to the coated treatments. Starr and DeRoo (1981) found similar results in a study in which they looked at N uptake of $(\text{NH}_4)_2\text{SO}_4$ by Kentucky bluegrass-red fescue (*Festuca rubra* L.). They found that N uptake of this uncoated N source primarily took place within the first 3 weeks after application. They further stated that most of the N uptake which took place from 3 to 9 weeks was derived from the soil N pool.

Urea treatments. Bermudagrass N uptake during the first 32 days exhibited no differences in response to coating urea. Cumulative N uptake by bermudagrass at 65 days still showed no differences in response to the different coating thicknesses. Total bermudagrass N uptake was 68 g N plot⁻¹ in response to C Urea-10 or 75% of total N uptake, 61 g N plot⁻¹ or 76% of total N uptake in response to C Urea-4.8, and 49 g N plot⁻¹ or

78% of total N uptake in response to uncoated urea. No differences in bermudagrass N-uptake were detected until the 80th day of the experiment. At this time, differences in N uptake were observed between C Urea-10 and uncoated urea. These differences persisted throughout the remainder of the 104 day experiment.

In a study conducted by Christianson (1988) comparing N release from reactive-layer coated urea with varying coating thicknesses, the rate of N release varied depending on coating thickness. He found that the granules with a thicker coating released urea at a slower rate. These findings would suggest that N uptake by bermudagrass should vary depending on the coating thickness of the N source applied to the turfgrass. However, N uptake data for the 1992 field experiment generally showed no differences in N uptake from the urea treatments.

Quality Ratings

One of the primary functions of N fertilization in turfgrass is the production of a high quality turf. A subjective measure of turf quality is turf color and density. One of the objectives of the utilization of controlled release N fertilizers is to prolong the quality of turf without need for frequent applications of N. During the 104 day field experiment, quality ratings of bermudagrass were recorded on a bi-weekly basis on a scale of 1 to 9, with 9 representing a superior quality turf, 1 representing brown or dead turf, and 5.5 representing minimum acceptable quality turf (Table 4-4).

Ammonium sulfate treatments. Bermudagrass quality was affected by treatment application throughout the experiment. Coated AS-4.7 produced the highest quality turfgrass, followed by uncoated AS. Coated AS-9.8 produced the lowest quality turfgrass, which is in agreement with the N uptake and growth data. Hummel (1989) obtained visual quality results similar to those produced by CAS-9.8 when resin-coated urea-270 (RCU-270) was applied to Kentucky bluegrass. He concluded that RCU-270 released N too slowly to produce turfgrass color comparable to the other treatments used in his experiment.

However, all treatments produced an acceptable quality

Table 4-4. Visual quality rating of bermudagrass following N application.

Treatment	Days After Application						
	14	28	42	56	70	84	98
AS	8.3a	8.7a	9.0a	8.0b	8.0b	7.3a	7.3a
CAS-4.7	8.0a	8.3a	9.0a	9.0a	9.0a	6.7a	6.7a
CAS-9.8	7.7a	7.0b	8.0b	7.3c	7.3c	6.3a	6.7a
CV**	9	6	0	4	4	8	8
Urea	8.0a	8.0a	8.3a	7.7a	7.3a	7.7a	7.7a
CUrea-4.8	8.7a	8.3a	8.3a	7.7a	7.3a	6.7a	6.3a
CUrea-10	7.7a	8.0a	8.3a	8.0a	8.0a	7.3a	7.0a
CV	9	4	7	6	6	8	11

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅; **Coefficient of variation (%).

of turfgrass. Differences in turfgrass quality between CAS-9.8 and the other two treatments were detected at 28, Table(4-4) and 42 days after N fertilizer application. Coated AS-4.7 sustained the highest quality turf through the 70th day of the experiment. During this same time period, the effect of the other two treatments on turf quality declined and no differences between these two treatments could be detected subsequently. After the 70th day all treatment affects on turf quality diminished, resulting in no differences in turf quality.

Urea treatments. Unlike the ammonium sulfate treatments, differences in turfgrass quality for plots receiving the urea treatments were not detected until the 42nd day of the experiment. Both coated urea treatments showed differences when compared to uncoated urea at this time. However, these differences were not sustained for the remainder of the experiment. Overall, C Urea-10 produced the highest quality turfgrass, followed by C Urea-4.8 and uncoated urea. Bermudagrass quality response to the urea treatments followed the same trend as growth and N uptake for this treatment group.

Experiment 2: 1993

Materials and Methods

This field study was conducted on established Tifway bermudagrass (Cynodon transvaalensis Burt-Davy X C. dactylon (L) Pers.) at the G.C. Horn Turfgrass Field Laboratory in

Gainesville, Florida between the months of June and August, 1993. Treatments (Table 4-5) were arranged in a randomized complete block design, replicated three times.

Table 4-5. Nitrogen treatment specifications (1993).

Treatment	% Coating
Urea	0
Coated Urea (CUrea-6)	6
Coated Urea (CUrea-12)	12

Each treatment was applied to a 2 x 3 meter turf plot maintained at a 2 cm mowing height. Treatments were applied at a rate of 1.5 Kg N 100 m⁻². All clippings were collected on a weekly basis, with a total of 8 harvests being collected during the 65 day experiment. Clippings were weighed to determine growth and digested for total Kjeldahl nitrogen (TKN) analysis, using a Rapid Flow Analyzer (RFA). Visual quality ratings were taken weekly for turfgrass quality evaluation. Statistical analysis of data was performed using Statistical Analysis System (SAS) procedures. The least significant difference (LSD) method was used for means separation.

Results and Discussion

Bermudagrass Growth

Bermudagrass growth was determined during the 65 day period by collecting all grass clippings on a weekly basis. Cumulative growth of the "Tifway" bermudagrass is summarized

in Table 4-6. Bermudagrass growth, 21 days after treatment application, was highest for uncoated urea, followed by C Urea-6 and C Urea-12. Uncoated urea produced a growth 5 times higher than C Urea-6 and 11 times higher than C Urea-12 during this time period. Growth by 29 days following treatment application differed for each treatment. Uncoated urea continued to have the highest growth among the treatments, producing 13 times higher growth than C Urea-12 during this time period. An increase in release of N from C Urea-6 narrowed the margin of difference in growth between this treatment and uncoated urea. However, uncoated urea still produced 2 times as much bermudagrass growth.

Table 4-6. Cumulative growth of bermudagrass following N application (g plot⁻¹)^{*}.

Treat- ment	----- Days After Application -----							
	12	21	29	36	43	50	57	65
Urea	39a	374a	575a	773a	944a	1106a	1200a	1289a
CUrea-6	9b	70b	291b	584a	830a	1056a	1200a	1310a
CUrea-12	14b	34b	45c	92b	176b	293b	388b	490b
CV**	38	15	21	17	15	14	12	11

^{*}Mean values within each column followed by the same letter are not significantly different according to LSD₀₅.

^{**}Coefficient of variation (%).

Midway through the experiment, bermudagrass growth was at 59% of its total growth in response to uncoated urea, followed by

45% of the total growth for bermudagrass receiving C Urea-6. Bermudagrass receiving C Urea-12, on the other hand, was only at 19% of its total growth by the 65th day of the experiment. Statistical analysis revealed that uncoated urea and C Urea-6 produced the same cumulative bermudagrass growth at this stage, and continued to produce the same cumulative growth throughout the remainder of the experiment.

Fifty days after application of uncoated urea, bermudagrass growth was at 86% of its total growth for the experiment, followed by 81% for C Urea-6. Coated Urea-12, on the other hand, had produced only 60% of the total bermudagrass growth during this same time period. At the end of the 65 day period, cumulative growth of bermudagrass in response to both uncoated urea and C Urea-6 was the same, but the total growth in response to C Urea-12 was only 37% of that produced by C Urea-6. However, 40% of the total growth produced by C Urea-12 was produced during the last 15 days of the experiment. This indicates the increased (or at least sustained) release of N from this heavily coated material during the latter part of the experiment.

Nitrogen Uptake

Nitrogen uptake for the applied urea treatments during the 65 day experiment is summarized in Table 4-7. Uptake of applied N by the bermudagrass followed the same pattern as growth. Uncoated urea resulted in the highest initial N uptake, followed by the two coated treatments. This trend was

maintained throughout the first 29 days. Statistical analysis of data for the third harvest indicated an increase in N uptake for bermudagrass receiving C Urea-6 material, which was sustained throughout the remainder of the experiment. Forty three days after treatment application, N uptake for bermudagrass receiving C Urea-6 surpassed that by bermudagrass receiving uncoated urea. This would suggest an increase in available N from the C Urea-6 treatment and a depletion of available N from the uncoated urea.

Bermudagrass receiving C Urea-12 had very low N uptake compared to the other two treatments, throughout the experiment. The data suggest that N uptake may have been impeded by

Table 4-7. Cumulative N uptake by bermudagrass following N application (g plot⁻¹).

----- Days After Application -----								
Treat- ment	12	21	29	36	43	50	57	65
Urea	a* 1.95	a 14.5	a 20.7	a 27.2	a 31.6	a 35.7	a 38.0	a 40.5
CUrea- 6	b 0.21	b 2.64	b 11.6	a 23.9	a 31.9	a 38.9	a 43.7	a 47.6
CUrea- 12	b 0.29	b 0.75	c 0.99	b 2.18	b 4.47	b 7.74	b 10.7	b 14.4
CV**	25	23	30	13	16	15	15	29

*Mean values within each column followed by the same letter are not significantly different according to LSD₀₅.

**Coefficient of variation (%).

the slow N-release rate for this material. A similar observation was made by Hummel (1989) during a study to evaluate differentially coated RLC urea materials. He concluded that the heavily coated material (RCU-270) released N too slowly to produce sufficient N uptake and growth.

Percent of total N uptake at 21 (N₂) and 43 days after N application clearly identifies the effect of coating on N uptake by bermudagrass. Cumulative N uptake at 21 days showed 36% of the total N uptake for bermudagrass receiving uncoated urea and 5.5% of total N uptake for the two coated treatments. However, after 43 days, the N uptake values were 78%, 67% and 31% of total N uptake by bermudagrass receiving uncoated urea, C Urea-6 and C Urea-12, respectively. Overall N uptake was highest for bermudagrass receiving C Urea-6 and uncoated urea, even though uncoated urea had the highest N uptake for the first half of the experiment.

One explanation for the lower N uptake produced by the thickly coated urea treatment (12%) is the effect of soil moisture on the release of N. Less rainfall occurred during the 1993 experimental period, possibly influencing the release of N from the coated materials. The volumetric water content of the soil, effects the release process directly as it effects the diffusion of N through the coating membrane. Therefor, the greater the soil moisture content, the greater the release of N from the coating resulting in more N available for plant uptake.

Visual Quality

Bermudagrass visual quality ratings are summarized in Table 4-8. Uncoated urea produced the highest visual quality of bermudagrass for the first 21 days of the experiment.

Table 4-8. Visual quality rating of bermudagrass following N application.

Treat- ment	----- Days After Application -----							
	12	21	29	36	43	50	57	65
Urea	a* 8.0	a 8.3	a 8.0	b 7.7	b 8.0	b 6.7	c 6.0	c 6.0
CUrea- 6	b 6.0	b 6.7	a 8.0	a 9.0	a 9.0	a 8.0	b 7.0	a 8.0
CUrea- 12	b 6.3	b 5.7	b 5.7	c 6.3	c 7.3	a 7.7	a 7.7	a 7.3
C.V.**	4.9	8.4	4.6	6.1	4.1	6.3	4.8	4.9

*Mean values within each column followed by the same letter are not significantly different according to LSD_{05} .

**Coefficient of variation (%).

Visual quality for bermudagrass receiving C Urea-6 matched that of bermudagrass receiving uncoated urea 29 days after application. This is most likely the result of an increase in available N from the C Urea-6. Thirty six days after treatment application, visual quality for bermudagrass receiving uncoated urea began to diminish as the available N from this source was depleted. Coated Urea-12 produced a lower-visual quality bermudagrass for the first 43 days of the experiment.

However, visual quality of the bermudagrass receiving C Urea-12 increased during the last three weeks of the experiment.

This corresponds to findings made by Peacock and DiPaola (1992). In a study comparing the effects of different coating thicknesses for RLC urea on visual quality of bermudagrass, they observed that urea treatments with greater than 10% coating had a delayed effect on visual quality. They recommended that a soluble N source be mixed with these heavily coated materials to increase the visual quality of the bermudagrass more rapidly after application.

Summary and Conclusions

Experiment 1

Bermudagrass growth and N uptake in response to coating urea differed from those obtained coating AS. No differences in growth or N uptake were detected in response to the two coated urea treatments until late in the experiment. However, differences between the two coated AS treatments were detected at 65 days. The data suggest that these differences are related to different release rates of the encapsulated N. Findings from the N release-rate study discussed in Chapter 3 revealed that urea has a higher release rate compared to AS with the same coating thickness. This is the result of the higher solubility of urea compared to AS, along with the more profound effect of temperature on urea's solubility and subsequent release. Uncoated AS and urea produced similar cumulative growth and N uptake in bermudagrass.

Coating these N substrates resulted in an overall increase in growth and N uptake by bermudagrass with the exception of CAS-9.8. Coating AS with a 9.8% coating obstructed N release and resulted in overall lower N uptake for this treatment. In general, however, coating the N substrate resulted in increased growth and N uptake compared to the uncoated treatments. These increases reflect a direct influence of coating on release of the N substrate, resulting in a higher growth and N uptake.

Visual quality of the bermudagrass was also affected by coating the N substrates. Coated AS-4.7 produced the most uniform and highest quality bermudagrass throughout the experiment. Uncoated AS produced its highest quality rating at 42 days and then steadily declined throughout the remainder of the experiment. This represents the normal pattern of quality for uncoated materials. With the exception of CAS-9.8, the ammonium sulfate group produced higher quality bermudagrass when compared to the urea treatments. One explanation is that the urea treatments produced a higher growth and N uptake resulting in a dilution of N concentrations in the turfgrass. This dilution effect resulted in a lower quality turfgrass. Bermudagrass response to the urea treatment group was not as profound as for the ammonium sulfate treatments. All the urea treatments produced the same quality of bermudagrass regardless of coating, suggesting that the high release rates of both coated urea treatments produced

the same quality turfgrass as uncoated urea. However, bermudagrass quality was acceptable throughout the experiment for all treatments. Quality ratings never reached the minimum acceptable level of quality for any of the treatments.

Experiment 2

Differences between the two coated urea treatments were observed early in the experiment. Coated Urea-12 produced lower N uptake and growth than the other two urea treatments. Data indicate that the 12% coating on urea impeded the N release, resulting in lower N uptake and growth. As a result, visual quality of the bermudagrass receiving this treatment was lower compared to bermudagrass receiving the other urea treatments.

Coating urea with a 6% coating resulted in higher N uptake, growth and visual quality when compared to C Urea-12. However, no differences in N uptake and growth between uncoated urea and C Urea-6 were detected. One explanation is the low rainfall experienced during the experiment in 1993, resulting in lower leaching losses than would be typical for the uncoated material. Results from the lysimeter study (Chapter 5) indicated that no leaching of N occurred during the 1993 experimental period, as a result of low rainfall.

CHAPTER 5
UPTAKE AND LEACHING OF REACTIVE-LAYER COATED
¹⁵N AMMONIUM SULFATE AND UREA

Introduction

Nitrogen, once introduced into the soil, undergoes several dynamic transformations which constitute the N Cycle. It is these interconnected transformations which make N difficult to study in the soil/plant system. However, there is both an economic, as well as an environmental, need to determine the fate of N in turfgrass ecosystems. Numerous techniques have been used to investigate the fate of N. However, most studies have focused on a single process within the N cycle. In order to examine N transformations as an interacting unit it is necessary to trace N through the various components of the N cycle.

Through the use of lysimetry and ¹⁵N tracers, information regarding the partitioning of applied N in various ecosystems can be gained. These research tools can provide information regarding N uptake, soil retention, and leaching characteristics of applied N to turfgrass.

Nitrate contamination of groundwater has led to increasing public concern and consequently a need for more research investigating the fate of applied N fertilizers. Research is

focused on better understanding of N in the soil/plant system with an emphasis on increasing the use efficiency of N and reducing its leaching potential. Controlled-release fertilizers, and particularly Reactive-Layer Coated N sources, have been designed to extend the supply of N to the plant through controlled release of the nutrient, consequently reducing leaching through higher uptake efficiency.

A field lysimeter study using ^{15}N labeled material was designed with the following objectives: 1) to determine the effect of ^{15}N labeled $(\text{NH}_4)_2\text{SO}_4$ and urea with different coating thicknesses on growth of, and N uptake by bermudagrass; 2) to quantify bermudagrass uptake of N from applied N sources; 3) to investigate leaching characteristics of the applied N sources and the influence of coating type and coating thickness on N leaching; and 4) to determine $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ concentrations in the unsaturated and saturated zones underlying the fertilized lysimeters, including their impact on shallow groundwater.

Materials and Methods

A field lysimeter study was conducted at the G.C. Horn Turfgrass Field Research Laboratory at the University of Florida in Gainesville, Fl. Twenty four open-ended lysimeters were constructed from PVC pipe 61 cm in diameter and cut to 122 cm length (Figure 5-1). A 15m X 15m area of Tifway bermudagrass (Cynodon transvaalensis Burt-Davy X C. dactylon (L) Pers.) established on Arredondo Fine Sand (siliceous,

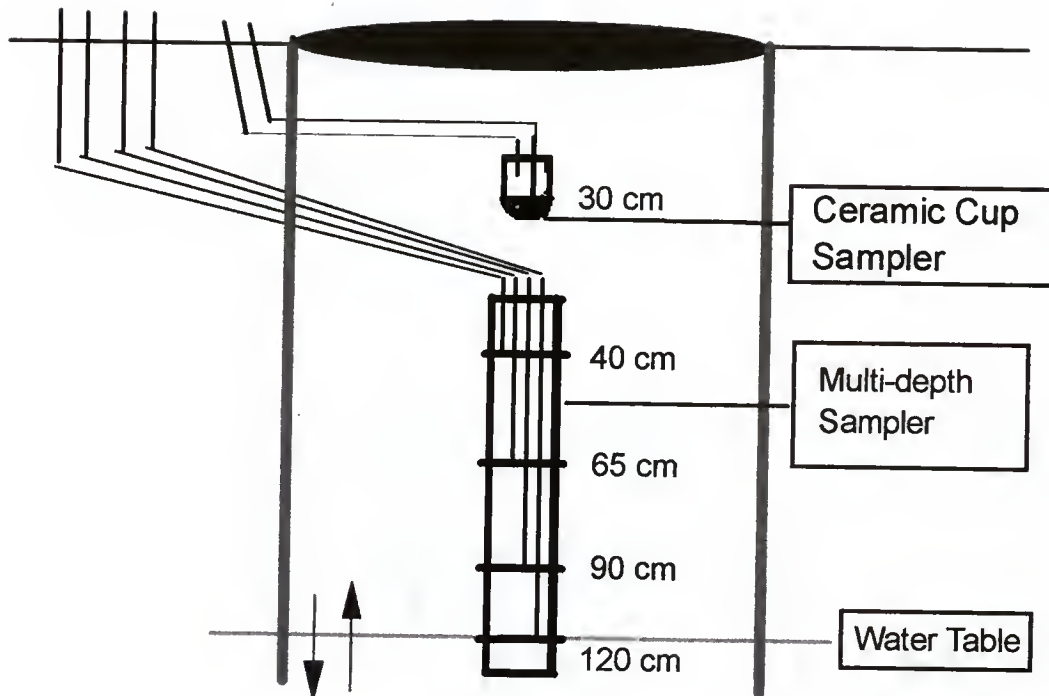


Figure 5-1. Open-end lysimeter with multi-depth sampler

hyperthermic Grossarenic Paleudults) was selected for this study. The location of each lysimeter was prepared for installation through the removal of core samples, 1.25 cm in diameter, around the perimeter of the lysimeter and to a depth of 100 cm. Each lysimeter was hydraulically pressed to a depth of 120 cm. Installation was done in such a manner as not to disturb the soil column contained within the lysimeter. This lysimeter depth was chosen because the water table at the experimental site fluctuates approximately between the 120 cm and 90 cm depth.

Two types of devices were used for sampling leachate from within the lysimeter. A ceramic cup sampler 6 cm in diameter and 5.4 cm in length was used to sample soil solutions from the intermediate vadose zone at the 30cm depth. In anticipation of a fluctuating water table, a multi-depth sampler was also constructed in order to sample the saturated zone. The sampler was constructed from PVC pipe 5 cm in diameter and 90 cm long. Four sampling ports were installed in the PVC pipe to take water samples at the 45, 70, 95 and 120 cm depths whenever the soil was saturated. Polyethylene tubing was connected to the four sampling ports and the tubing was pulled to the surface. A core sample extending through the center of each lysimeter was extracted using a hydraulic core sampler equipped with a plastic liner for maintaining intact core samples. These core samples were sectioned and analyzed for pre-study chemical and physical analysis (Tables 5-1, 5-2 and

5-3). The sampler was then placed in the center of the lysimeter where the core sample was removed. The multi-depth sampler was placed so that the sampling ports were located 45 cm, 70 cm, 95 cm, and 120 cm from the soil surface. A layer of soil was then placed on top of the multi-depth sampler and the ceramic cup sampler was positioned at 30 cm below the surface. A slurry of Arredondo fine sand was poured around the samplers so that there would be maximum contact with the soil. All sampling tubes were brought to the edge of the lysimeter and pulled to the surface through holes drilled 15 cm from the top of the lysimeter.

Labeled ^{15}N $(\text{NH}_4)_2\text{SO}_4$ and urea (5 atom % ^{15}N) were pelletized by the Tennessee Valley Authority (TVA) in order to facilitate the Reactive-Layer Coating process. Ammonium sulfate and urea were coated with two different coating thicknesses (Table 5-4). In addition to the coated treatments, both substrates were applied in uncoated form as well. These 6 treatments were applied to the bermudagrass in 4 replications, using a complete randomized block design. Treatments were applied at $1.5 \text{ kg N } 100 \text{ m}^{-2} \text{ yr}^{-1}$ with the labeled ^{15}N materials being applied once, in the first year.

Study design, construction, and installation was completed in December of 1991, with the study being initiated in May of 1992. Irrigation was maintained to meet estimated evapotranspiration (ET) rates. During the growing season,

Table 5-1. Selected soil chemical and physical properties of the bermudagrass site.

Depth (cm)	TKN (mg kg ⁻¹)	pH	Bulk Density (g cm ⁻³)	Porosity (%)
0-15	543* (318-698) ⁺	6.5 (6.1-6.8)	1.26 (1.05-1.52)	52 (43-60)
15-30	216 (148-275)	6.4 (6.1-6.8)	1.49 (1.37-1.63)	44 (39-48)
30-60	135 (63-148)	6.4 (6.2-6.6)	1.50 (1.35-1.62)	43 (39-49)
60-90	117 (63-148)	6.1 (5.8-6.6)	1.61 (1.45-1.69)	39 (36-45)

*Mean of 24 samples; ⁺Range of values;

Table 5-2. Total N and C:N ratios in the bermudagrass root-zone soil.

Depth (cm)	TKN (mg kg ⁻¹)	C:N
0-5	1371* (1000-1730) ⁺	13.1 (11.6-15.0)
5-15	470 (310-650)	17.0 (14.0-21.3)

* Mean of 24 samples; ⁺Range of values;

Table 5-3. Selected soil chemical properties of bermudagrass root-zone soil.

Depth (cm)	Ca (mg kg ⁻¹)	Mg (mg kg ⁻¹)	K (mg kg ⁻¹)	P (mg kg ⁻¹)
0-5	1508* (1184-1948) ⁺	113 (83-163)	41.8 (24.8-56.0)	204 (155-282)
5-15	942 (568-1196)	80 (44-108)	28.0 (15.2-50.0)	230 (201-277)

*Mean of 24 samples; ⁺Range of values;

rainfall and irrigation, and soil and ambient air temperatures were recorded (APPENDIX). Bermudagrass was maintained at a height of 2.5 cm. Grass clippings were collected on a weekly basis for 90 days during the bermuda- grass growing period. Clippings were analyzed for total Kjeldal nitrogen (TKN) (Bremner and Mulvaney, 1982) and ^{15}N using a Rapid Flow Analyzer and a mass spectrometer (Hauck, 1982), respectively.

Table 5-4. Nitrogen treatment specifications.

Treatment	N Substrate	% Coating
$(\text{NH}_4)_2\text{SO}_4$ (AS)	$(\text{NH}_4)_2\text{SO}_4$	0
Coated AS (CAS-4.7)		4.7
Coated AS (CAS-9.8)		9.8
Urea	UREA	0
Coated Urea (CUrea-4.8)		4.8
Coated Urea (CUrea-10)		10

A manifold connected to a vacuum pump was used to collect soil solution samples at depths of 30 cm, 95 cm and 120 cm simultaneously. These samples were analyzed for $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$. Samples collected from the lysimeters receiving urea treatments were also analyzed for urea during the first two weeks of the experiment. Soil, thatch, and root samples were collected at the end of each growing season and analyzed for TKN and ^{15}N .

Bermudagrass N recovery was determined using the ^{15}N tracer method according to Hauck and Bremner (1976) and also the difference method (chapter 2). Recovery of applied N in soil and thatch was determined by the ^{15}N tracer method. Statistical analysis of data was performed using Statistical Analysis System (SAS) procedures. The least significant difference (LSD) method was used for means separation.

Results and Discussion

Bermudagrass Growth

Tifway bermudagrass growth was affected by the N substrate and coating thickness of the applied N fertilizer (Table 5-5). Coated urea with a 10% coating (C Urea-10) and coated ammonium sulfate with a 4.7% coating (CAS-4.7) produced the highest bermudagrass growth, followed by coated urea with a 4.8% coating (C Urea-4.8). Uncoated AS and urea had similar growth patterns, with AS producing a slightly higher overall growth. Coated AS with a 9.8% coating (CAS-9.8) produced the lowest bermudagrass growth.

Bermudagrass growth is affected by several factors, including the available N pool, the growth cycle of bermudagrass, temperature and rainfall (Hummel and Waddington, 1984). Growth data suggest that these factors produced an overall net effect on the growth rates according to the magnitudes and degrees of interaction between the respective factors .

Ammonium sulfate treatments. During the first 30 days after treatment application, differences in growth were

observed in response to the three AS treatments. Uncoated AS produced the highest growth during this time period. Lysimeters receiving uncoated AS produced 58% of their total growth during the first 30 days of the experiment. This may be the result of the quick availability of applied N in this substrate form. Coated AS-4.7 produced the second highest rate of growth among the AS treatments, followed by CAS-9.8.

Table 5-5. Growth of Tifway bermudagrass following N application (g lysimeter^{-1}).

Treatment	Monthly Growth at			Total Growth
	30d	60d	90d	
AS	18.7a ⁺	11.1b	2.6b	32.3a
CAS-4.7	8.9b	17.3a	10.0a	36.2a
CAS-9.8	2.7c	4.9c	4.7b	12.3b
Urea	16.9a	8.9b	4.0b	29.8a
CUrea-4.7	11.4b	15.5a	7.4a	34.3a
CUrea-10	8.8b	17.2a	10.3a	36.3a

+ Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD_{05} .

Bermudagrass growth in response to these two treatments was affected by the different coating thicknesses. Application of CAS-4.7 resulted in 25% of the total bermudagrass growth during this 30 day period. Coated AS-9.8 produced 22% of the total bermudagrass growth during this same period. The higher

growth in response to CAS-4.7 probably reflects the higher release rate of N with this thinner coating thickness compared to CAS-9.8.

During the second 30 days, CAS-4.7 produced the highest bermudagrass growth among the AS treatments, resulting in 48% of total growth. Uncoated AS followed producing 34% of its total bermudagrass growth during this 30 day interval. Coated AS-9.8 again produced the lowest bermudagrass growth.

During the 60 to 90 day period of the bermudagrass growing season, no differences in growth between uncoated AS and CAS-9.8 were detected. Uncoated AS produced the lowest growth, accounting for only 8% of total growth. However, coated AS-9.8 produced 38% of its total bermudagrass growth during this same time period. No differences were detected between these two treatments because growth resulting from uncoated AS decreased substantially, and the growth rate for bermudagrass receiving CAS-9.8 was maintained. Bermudagrass growth in lysimeters receiving CAS-4.7 decreased, resulting in only 27% of the total seasonal bermudagrass growth. However, CAS-4.7 maintained a reasonable growth rate during this period.

Urea treatments. During the first 30 days after treatment application, differences in growth were observed between the uncoated treatment and the two coated urea treatments. Uncoated urea produced the highest growth during this time period, with lysimeters receiving uncoated urea producing 57% of their total growth during the first 30 days of the experi-

ment. No differences among the two coated urea treatments were detected. Application of C Urea-4.8 resulted in 33% of total seasonal bermudagrass growth during this 30 day period, while C Urea-10 produced 24% of total seasonal bermudagrass growth during this same period. Though C Urea-4.8 produced a higher growth rate than C Urea-10, these differences were not significant.

During the second 30 days, growth resulting from application of uncoated urea was reduced, for the N supply from this uncoated N source was nearly depleted as a result of high initial uptake. Therefore, uncoated urea only produced 30% of its total growth during this period, resulting in the lowest growth among the three urea treatments. While the coated urea treatments produced the highest growth, statistical analysis revealed no differences between them. Bermudagrass growth in response to coated Urea-4.8 was 45% of total seasonal growth during this period, while C Urea-10 produced 47% of total seasonal bermudagrass growth during this same 30 day period.

During the 60 to 90 day period, the coated urea treatments again produced the highest growth of bermudagrass, though no differences between the two treatments were detected. Coated Urea-4.8 produced 22% of total seasonal bermudagrass growth, while C Urea-10 produced 29% of total seasonal bermudagrass growth. Lysimeters receiving uncoated urea produced the lowest growth, with only 13% of total growth being produced during the final 30 days of the season.

Nitrogen Uptake

Tifway bermudagrass N uptake was determined using both the Difference and tracer methods. Both methods revealed that Tifway bermudagrass N uptake was affected by coating thickness and subsequent N release rate of the applied N fertilizer, as well as by growing conditions. Similar results were reported by Hummel and Waddington (1981) and Hummel and Waddington (1984). The N uptake pattern for bermudagrass was similar to that of growth. Both coated urea treatments produced the highest N uptake, followed by CAS-4.7. Uncoated urea and AS produced the same N uptake by bermudagrass. Coated AS-9.8 produced the lowest N uptake throughout the bermudagrass growing season.

Ammonium sulfate treatments. During the first 30 days after fertilization, differences in N uptake were observed in response to the three AS treatments (Table 5-6). Using both the Difference and Tracer methods, uncoated AS produced the highest growth. This is consistent with the findings of Waddington et al. (1985). In their study initial "flushes" of growth and N uptake were observed in response to the application of $(\text{NH}_4)_2\text{SO}_4$.

However, the effects from the applied N quickly waned in this case, due to the soluble nature of these materials. Bermudagrass receiving uncoated AS produced 67% of its total N uptake during the first 30 days of the experiment, according to the ^{15}N Tracer method. When data were calculated using the

Table 5-6. Nitrogen uptake calculated using the ^{15}N tracer and difference methods ($\text{mg N lysimeter}^{-1}$).

Treatment	NUP*30		NUP60		NUP90	
	^{15}N	Diff.	^{15}N	Diff.	^{15}N	Diff.
AS	969 a ⁺	845 a	370 b	424 b	115 c	129 c
CAS-4.7	497 b	345 b	800 a	725 a	537 a	525 a
CAS-9.8	77 c	107 c	185 c	253 c	228 b	325 b
Urea	965 a	732 a	360 b	324 b	145 c	210 c
CUrea-4.8	752 b	547 b	931 a	698 a	420 b	405 b
CUrea-10	393 c	434 b	1062a	887 a	724 a	709 a

- * NUP30, NUP60 and NUP90=monthly N uptake at 30, 60 and 90 days.
 + Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD_{05} .

Difference method, N uptake for this period was 63% of the total N uptake. The high initial N uptake is the result of the rapid availability of applied N in this substrate form. Coated AS-4.7 produced the second highest N uptake among the AS treatments, followed by CAS-9.8. Bermudagrass N uptake in response to these two treatments was affected by coating thickness. Based on the ^{15}N Tracer method, application of CAS-4.7 resulted in 28% of total bermudagrass N uptake during this 30 day period. This percentage was slightly different, 24%, when N uptake data were calculated using the Difference method. Coated AS-9.8 produced 15.8% of total bermudagrass N uptake according to the ^{15}N Tracer method and 18% according to the Difference method during this same period. The higher N uptake in response to CAS-4.7 reflects the higher release rate

of N with this lower coating thickness compared to CAS-9.8.

During the second 30 days, differences in N uptake among all three AS treatments were observed (Table 5-6) when data were calculated using the ^{15}N Tracer method. Coated AS-4.7 produced the highest bermudagrass N uptake among the AS treatments, resulting in 44% of total N uptake based on the ^{15}N Tracer method and 49% of total N uptake based on the Difference method. Uncoated AS followed CAS-4.7, producing 26% of total bermudagrass N uptake as calculated using the ^{15}N Tracer method, and 31% as calculated using the Difference method during this 30 day interval. The high N uptake produced by uncoated AS at 60 days further supports Waddington et al.'s (1985) observations, however, it appears to be inconsistent with the observations of Starr and DeRoo (1981). Starr and DeRoo (1981) conducted a study looking at N uptake from ^{15}N -labelled $(\text{NH}_4)_2\text{SO}_4$. They reported 20% to 30% of the applied N was recovered within 3 weeks after application, but dropped to nearly zero after that time.

Coated AS-9.8 again produced the lowest N uptake by bermudagrass. However, N uptake increased in response to this treatment during this 30 day interval. According to data calculated using the ^{15}N Tracer method, N uptake was 38% of total seasonal bermudagrass N uptake during this time period. Nitrogen uptake was determined to be 42% of the total using the Difference method.

During the final 30 day growth period, differences in N

uptake were detected among all of the AS treatments using both calculation methods. Uncoated AS produced the lowest N uptake, accounting for only 8% of total N uptake using the ^{15}N Tracer method and 6% using the Difference method. However, CAS-9.8 produced 47% of its total N uptake by bermudagrass during this same period according to the ^{15}N Tracer method and 40% by the Difference method. This indicates that the N release rate with this coating thickness increased during the final 30 day period resulting in higher N uptake. The N uptake by bermudagrass in lysimeters receiving CAS-4.7 decreased during this time period as the available N within the granules was depleted over time. Nitrogen uptake in response to this treatment was only 29% of the total bermudagrass N uptake for this period according to the ^{15}N Tracer method, and 27% according to the Difference method. However, CAS-4.7 maintained the highest rate of N uptake in bermudagrass.

Urea treatments. During the first 30 day after treatment application, differences in N uptake were observed among all of the urea treatments when the ^{15}N Tracer method was used to determine N uptake (Table 5-6). No differences between the two coated urea treatments were observed when the Difference method was employed to calculate N uptake. Uncoated urea produced the highest N uptake by bermudagrass during this time period. Bermudagrass receiving uncoated urea accumulated 66% of its total N uptake during the first 30 days of the experi-

ment according to the ^{15}N Tracer method. When data were calculated using the Difference method, N uptake was 61% of the total seasonal N uptake. Coated Urea-4.8 produced the second highest N uptake rate among the urea treatments, followed by C Urea-10. Nitrogen uptake by bermudagrass in response to these two treatments was affected by their different coating thicknesses when calculated according to the ^{15}N Tracer method. Based on this method, application of C Urea-4.8 resulted in 36% of total bermudagrass N uptake during this 30 day period. This percentage slightly differed, 35%, when N uptake data were calculated using the Difference method. Coated Urea-10 produced 18% of total seasonal bermudagrass N uptake using the ^{15}N Tracer method and 23% using the Difference method during this same period. The higher N uptake in response to C Urea-4.8 reflects the higher release rate of N from this lower coating thickness compared to C Urea-10.

During the second 30 days, differences in N uptake between uncoated urea and the two coated urea treatments were observed (Table 5-6) when data were calculated using either method. Coated Urea-10 produced the highest bermudagrass N uptake among the urea treatments resulting in 49% of total N uptake during this period based on the ^{15}N Tracer method and 47% based on the Difference method. Coated Urea-4.8 followed C Urea-10, producing 44% of total seasonal bermudagrass N uptake calculated using the ^{15}N Tracer method and 45% using the

Difference method. Uncoated urea produced the lowest N uptake in bermudagrass during this 30 day interval. According to data calculated using the ^{15}N Tracer method, N uptake was only 25% of the total bermudagrass N-uptake during this time period. Nitrogen uptake was determined to be 27% of the total using the Difference method.

During the final 30 day growth period, differences in N uptake were detected among all of the urea treatments using both calculation methods. Uncoated urea again produced the lowest N uptake, accounting for only 10% of total N uptake using the ^{15}N Tracer method and 13% using the Difference method. This is consistent with the findings of Landschoot and Waddington (1987) who found that one of the characteristics of uncoated urea is a high initial N uptake of only short duration. However, C Urea-10 produced 33% of total N uptake by bermudagrass according to the ^{15}N Tracer method and 31% according to the Difference method. Bermudagrass N uptake in lysimeters receiving C Urea-4.8 was only 20% of total seasonal bermudagrass N uptake according to the ^{15}N Tracer method, and 21% using the Difference method.

Leaching of Applied N

The concentrations of $\text{NO}_3\text{-N}$ in soil solution (at 30 cm) and water samples (at 90 cm and 120 cm) were determined and are presented in Figures 5-2 through 5-4. Water samples could not be collected at the 45 cm and 70 cm depths, due to unsaturated soil conditions. The soil solution and water samples

were also analyzed for $\text{NH}_4\text{-N}$ and urea; however, no $\text{NH}_4\text{-N}$ or urea was detected. This suggests that $\text{NH}_4\text{-N}$ may have been immobilized by the microbial population present in the turfgrass environment. Studies on mineralization and immobilization of soil N suggest that $\text{NH}_4\text{-N}$ is preferred by soil microbes over $\text{NO}_3\text{-N}$ (Jackson et al. 1989). In a study conducted by Jackson et al. (1989), data showed that daily uptake of $\text{NH}_4\text{-N}$ by plants and microbes was close to the actual size of the $\text{NH}_4\text{-N}$ pool. They found that ammonium was the dominant N source for both plants and microbes.

Ammonium Sulfate Treatments

Intermediate vadose zone (30 cm). A wide range of $\text{NO}_3\text{-N}$ concentrations was detected between the uncoated and coated AS treatments in the intermediate vadose zone (IVZ) at 30 cm. Nitrate-N concentrations at this depth began to increase rapidly, beginning at $32 \text{ mg L}^{-1} \text{ NO}_3\text{-N}$ at 11 days after fertilization with uncoated AS (Fig. 5-2). The highest concentration of $\text{NO}_3\text{-N}$ (189 mg L^{-1}) was detected 15 days after application. However, $\text{NO}_3\text{-N}$ concentrations decreased rapidly to 26 mg L^{-1} of $\text{NO}_3\text{-N}$ at 26 days after application. Nitrate concentrations were minimal for this treatment during the remainder of the experiment. These data suggest a rapid rate of nitrification for the uncoated AS.

The high $\text{NO}_3\text{-N}$ concentrations detected in the IVZ of lysimeters receiving uncoated AS during the first month of the experiment coincide with a high N uptake rate (67% of total N

uptake) in bermudagrass grown in these lysimeters . This suggests an excess of N in the root zone, resulting in both high N uptake by the plant and high $\text{NO}_3\text{-N}$ concentrations moving below the root zone concurrently.

Application of the coated AS treatments resulted in a lower overall $\text{NO}_3\text{-N}$ concentration in soil solutions at this depth when compared to uncoated AS. The highest concentration of $\text{NO}_3\text{-N}$ in soil solution from lysimeters receiving CAS-4.7 was 17 mg L^{-1} $\text{NO}_3\text{-N}$ at 13 days after application. Subsequently, $\text{NO}_3\text{-N}$ concentrations for this treatment decreased gradually and remained at minimal levels for the remainder of the experiment. The highest $\text{NO}_3\text{-N}$ concentration (9 mg L^{-1}) in soil solutions from lysimeters receiving CAS-9.8 were detected 31 days after treatment application.

Nitrate-N concentrations at the 90 cm depth.

Nitrate-N concentrations were lower at the 90 cm depth for all AS treatments. The highest concentration of $\text{NO}_3\text{-N}$ (20 mg L^{-1}) in water samples collected from lysimeters receiving uncoated AS was detected 19 days after fertilization. This is approximately 10 times lower than the highest $\text{NO}_3\text{-N}$ concentration detected at 30 cm for this treatment. In addition, it was detected 4 days later than the maximum $\text{NO}_3\text{-N}$ concentration detected at 30 cm. Another spike in $\text{NO}_3\text{-N}$ concentrations (11 mg L^{-1}) was also detected for this treatment at 31 days. This spike corresponds to rainfall events which occurred during

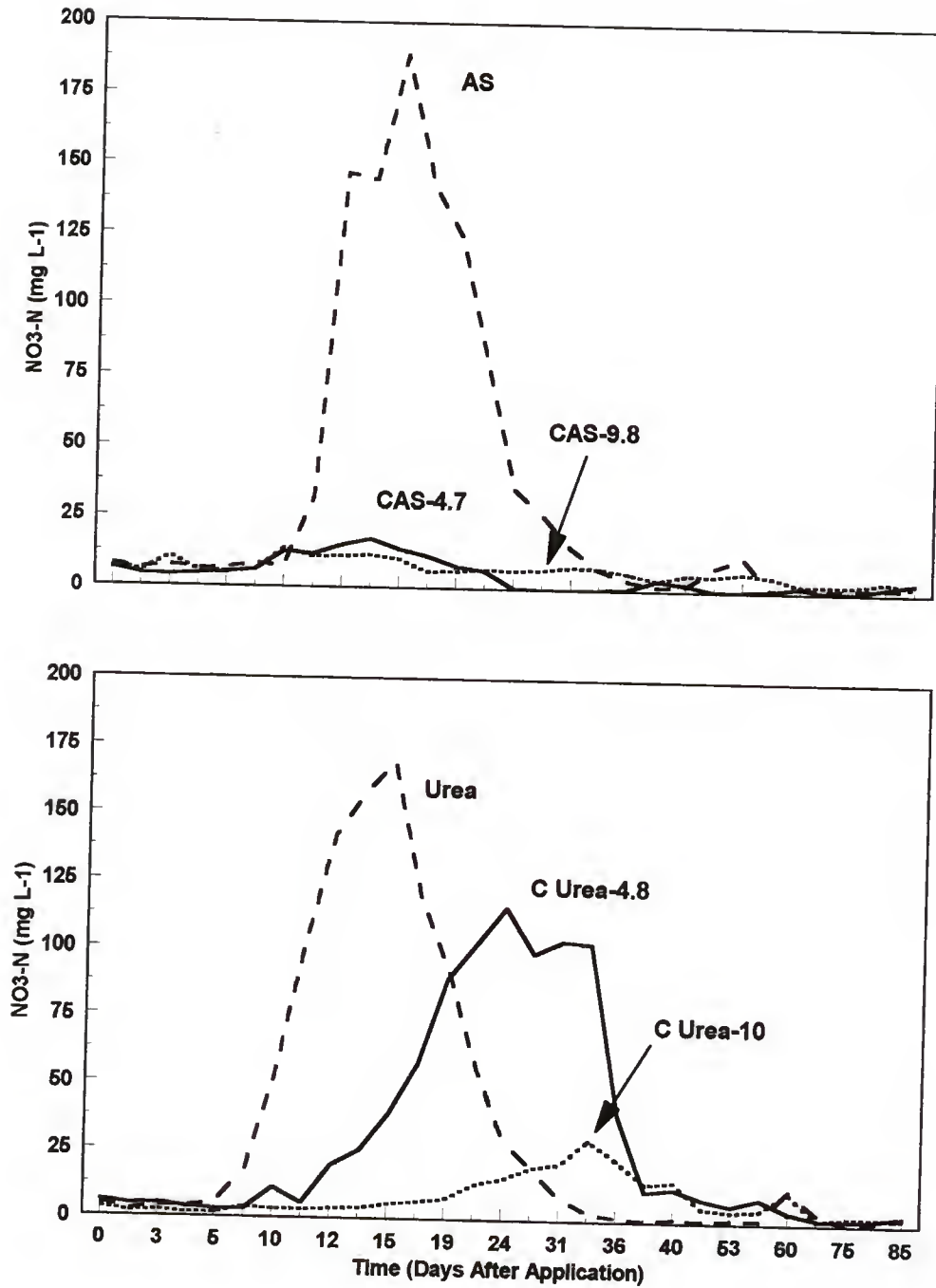


Figure 5-2. Effect of N substrate and coating thickness on $\text{NO}_3\text{-N}$ concentrations at the 30 cm depth.

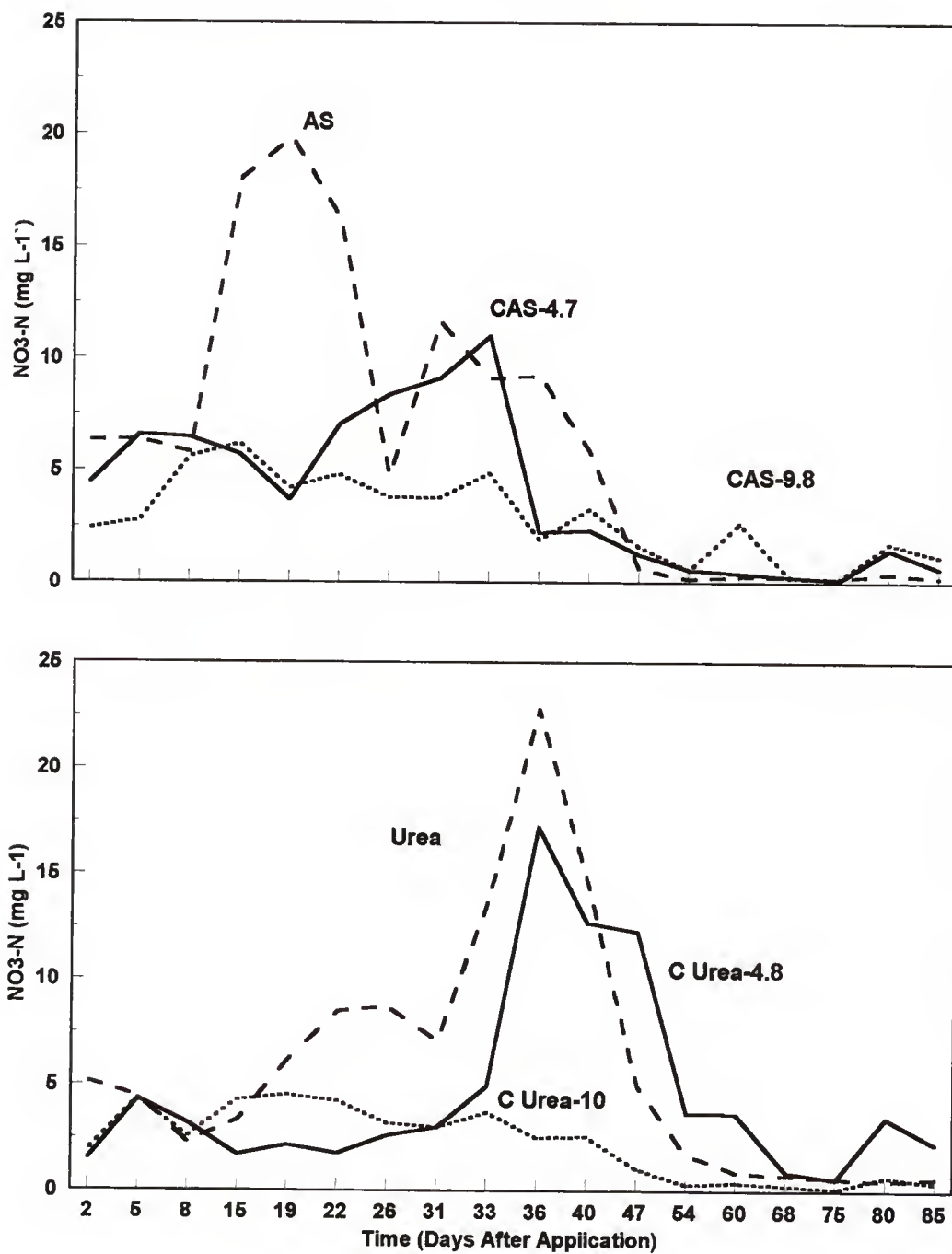


Figure 5-3. Effect of N substrate and coating thickness on $\text{NO}_3\text{-N}$ concentrations at the 90 cm depth.

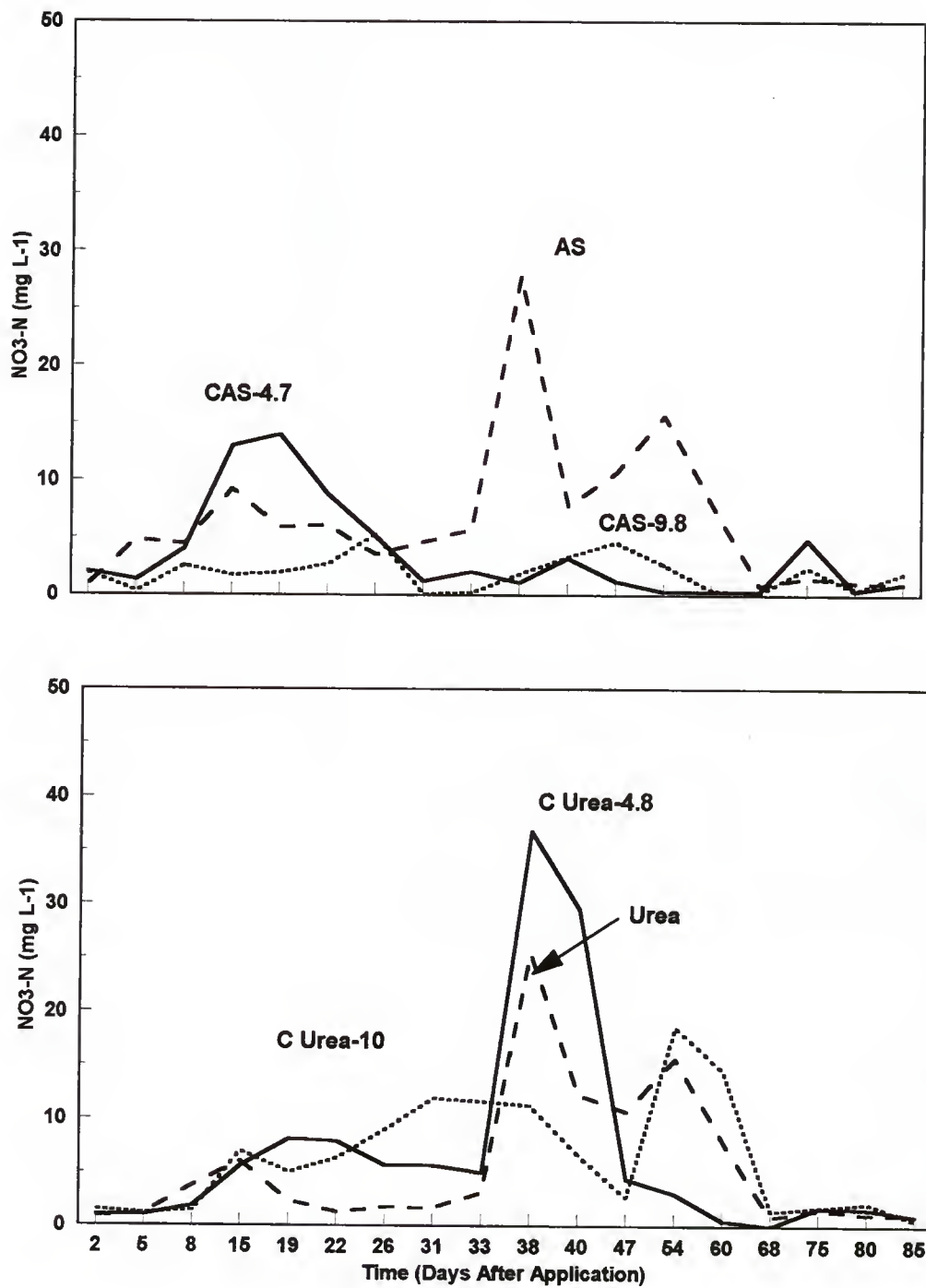


Figure 5-4. Effect of N substrate and coating thickness on $\text{NO}_3\text{-N}$ concentrations at the 120 cm depth.

this time, demonstrating the impact that rainfall can have on leaching of $\text{NO}_3\text{-N}$.

The lower $\text{NO}_3\text{-N}$ concentrations detected at this depth may be attributed to the dilution of $\text{NO}_3\text{-N}$ as it moves downward through the soil profile. Another possible mechanism that could have influenced $\text{NO}_3\text{-N}$ concentrations at this depth is denitrification. The fluctuating water table along with the presence of $\text{NO}_3\text{-N}$ may have presented favorable conditions for denitrification as a $\text{NO}_3\text{-N}$ removal mechanism at this depth.

The $\text{NO}_3\text{-N}$ concentrations in water samples from lysimeters receiving coated AS treatments were lower at this depth, remaining below 10 mg L^{-1} throughout the experiment with the exception of one sampling event. The sampling event 33 days after application showed a maximum $\text{NO}_3\text{-N}$ concentration of 11.5 mg L^{-1} in water samples from lysimeters receiving CAS-4.7.

Nitrate-N concentrations at 120 cm. Maximum $\text{NO}_3\text{-N}$ concentrations at the 120 cm depth (the water table level) were detected during the latter part of the experiment. Initial $\text{NO}_3\text{-N}$ concentrations remained below 10 mg L^{-1} during the first 33 days of the experiment with the exception of CAS-4.7. Water samples taken from lysimeters which received CAS-4.7 had maximum $\text{NO}_3\text{-N}$ concentrations of 13 mg L^{-1} and 14 mg L^{-1} on days 15 and 19, respectively. These elevated $\text{NO}_3\text{-N}$ concentrations coincided with high $\text{NO}_3\text{-N}$ concentrations detected for this same treatment at the 30 cm and 90 cm depths.

The highest $\text{NO}_3\text{-N}$ concentration (28 mg L^{-1}) were detected

38 days after application for uncoated AS. This was followed by a rapid decrease in $\text{NO}_3\text{-N}$ concentrations to less than 10 mg L^{-1} , and then an increase to 25 mg L^{-1} by the 54th day, mirroring the $\text{NO}_3\text{-N}$ concentration patterns which were detected during the earlier part of the experiment at the 90 cm depth for this treatment. Nitrate-N concentrations in water samples taken from lysimeters which received CAS-9.8 never exceeded above 5 mg L^{-1} .

Urea Treatment Group

Intermediate vadose zone (30cm). Elevated $\text{NO}_3\text{-N}$ concentrations in soil solution samples taken from lysimeters receiving uncoated urea were detected beginning 8 days after treatment application. Maximum $\text{NO}_3\text{-N}$ concentration was 169 mg L^{-1} $\text{NO}_3\text{-N}$ 15 days after treatment application for uncoated urea. Increases in $\text{NO}_3\text{-N}$ concentrations beginning 8 days after treatment application suggested that the nitrification rate of urea may be slightly faster than that for AS. However, maximum concentrations of $\text{NO}_3\text{-N}$ were detected on the same day for both of these uncoated N substrates. Nitrate-N concentrations then decreased rapidly to 19 mg L^{-1} by 26 days after application, and remained below 10 mg L^{-1} for the remainder of the experiment. The high $\text{NO}_3\text{-N}$ concentrations detected in the IVZ of lysimeters receiving uncoated urea during the first month of the experiment also coincided with a high rate of N uptake (66% of total N uptake) for bermudagrass grown in these lysimeters. Application of C Urea-4.8 rendered a

different leaching pattern than that of CAS-4.7. Elevated concentrations of $\text{NO}_3\text{-N}$ were detected in soil solution samples taken from lysimeters receiving this treatment, beginning 12 days after application. Nitrate-N concentrations continued to increase, reaching a maximum $\text{NO}_3\text{-N}$ concentration of 117 mg L^{-1} on the 24th day of the experiment. Nitrate-N concentrations then decreased to approximately 100 mg L^{-1} and were maintained at that level for 10 days before falling to below 10 mg L^{-1} on the 38th day of the experiment. The data suggest that coating urea with 4.8% coating resulted in a higher rate of N release when compared to the same thickness of coating on AS.

Nitrate-N concentrations remained below 20 mg L^{-1} for the first month after treatment application in soil solution samples taken from lysimeters receiving C Urea-10. The highest $\text{NO}_3\text{-N}$ concentration was detected at 33 days, at 30 mg L^{-1} $\text{NO}_3\text{-N}$ for this treatment. After 36 days, $\text{NO}_3\text{-N}$ concentrations dropped below 20 mg L^{-1} for the remainder of the experiment.

Nitrate-N concentrations at the 90 cm depth.

Nitrate-N concentrations were lower at the 90 cm depth compared to the concentrations at 30 cm for all urea treatments. Most notably, $\text{NO}_3\text{-N}$ concentrations in water samples taken from lysimeters receiving C Urea-10 never exceeded 5 mg L^{-1} . The highest concentration of $\text{NO}_3\text{-N}$ in water samples was detected for those samples collected from lysimeters receiving uncoated urea. The maximum $\text{NO}_3\text{-N}$ concentration (23 mg L^{-1})

was detected 38 days after treatment application. Nitrate-N concentrations in water samples taken from lysimeters receiving C Urea-4.8 peaked at 17 mg L^{-1} at 38 days, also. After 47 days, all $\text{NO}_3\text{-N}$ concentrations fell below 10 mg L^{-1} .

Nitrate-N concentrations at this depth were lower than those detected at the 120 cm depth. These lower $\text{NO}_3\text{-N}$ concentrations suggest $\text{NO}_3\text{-N}$ may be lost through denitrification as a result of the fluctuating water table. The comparison of $\text{NO}_3\text{-N}$ concentrations detected at the 90 cm and 120 cm depth suggest that $\text{NO}_3\text{-N}$ at the lower depth is less susceptible to denitrification.

Nitrate-N concentrations at the 120 cm depth. Initial $\text{NO}_3\text{-N}$ concentrations remained below 10 mg L^{-1} during the first 30 days of the experiment. Nitrate-N concentrations increased on the 38th day in samples taken from lysimeters receiving uncoated urea and C Urea-4.8, corresponding with heavy rainfall events during that time period. There was no increase in $\text{NO}_3\text{-N}$ concentrations in water samples taken from lysimeters receiving C Urea-10 during this same time period, suggesting that the thickly coated material is not as affected by rainfall as its more thinly coated counter-parts.

Nitrate-N concentrations of 12 mg L^{-1} were detected on the 31st day after fertilization in water samples taken from lysimeters which received C Urea-10. The $\text{NO}_3\text{-N}$ concentrations remained at this level until the 38th day, when concentrations dropped below 10 mg L^{-1} . On the 54th day, $\text{NO}_3\text{-N}$ concentrations

were detected at 18 mg L^{-1} for this treatment, corresponding to large rainfall events. All $\text{NO}_3\text{-N}$ concentrations were well below the EPA standard of 10 mg L^{-1} for the remainder of the experiment.

In general, coating AS and urea decreased leaching of $\text{NO}_3\text{-N}$ and lowered the $\text{NO}_3\text{-N}$ concentrations that did leach by regulating N release from the encapsulated N substrates. This suggests that using slow-release N sources will reduce or, in some cases, even eliminate $\text{NO}_3\text{-N}$ leaching from turfgrass. These findings are similar to findings by Brown et al. (1982) and Snyder et al. (1984).

Comparing the $\text{NO}_3\text{-N}$ concentrations leached with corresponding N uptake data (Table 5-3) for the same time period reveals a nexus between increased N uptake and an increase in $\text{NO}_3\text{-N}$ leached. This suggests that, as more N is available for plant uptake, the potential for leaching of the available N below the root zone increases with frequent rainfall and irrigation. This is consistent with the findings of Snyder et al. (1984).

Recovery of Applied N

Nitrogen uptake efficiency can be measured in terms of net recovery of N by the plant. Therefore, quantifying the distribution of N in the soil/plant system enables one to determine the fate of applied N and allows utilization of turfgrass management practices which will increase use efficiency of applied N and minimize N losses to the envi-

ronment. In this lysimeter study, applied N was recovered in plant tissue, stolons, roots, thatch, soil and as N percolated through the lysimeter (Table 5-7).

Recovery in clippings. Recovery of applied N in clippings varied according to N substrate and coating thickness. Nitrogen recovery was highest for bermudagrass receiving the coated urea treatments. Recovery of applied N in bermudagrass receiving C Urea-10 was 51%, followed by 49% recovery for C Urea-4.8. The recovery of applied N in clippings for lysimeters receiving CAS-4.7 was 43%. Percent recovery of applied N was the same, 34%, for clippings from bermudagrass receiving the uncoated AS and urea treatments. Coated AS-9.8 had the lowest recovery rate in clippings, accounting for only 11% of

Table 5-7. Percent recovery of applied ^{15}N -labeled N after 90 days.

Treatment	Clippings	Stolons & Roots	Thatch & Soil	Soil	Total
AS	34.0b*	7.0b	11.4a	1.9a	54.2b
CAS-4.7	42.9a	11.0a	9.0a	1.5a	64.4a
CAS-9.8	11.4c	5.2b	9.7a	0.8b	27.1c
CV**	9	22	16	41	7
Urea	34.3b	5.9a	13.9a	1.9a	56.0b
CUrea-4.8	49.2a	7.9a	11.4a	1.7a	70.2a
CUrea-10	51.0a	7.8a	11.4a	1.3a	71.5a
CV	10	37	21	62	7

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD_{05} ; **Coefficient of variation.

the applied N. This is consistent with the findings of Mosdell et al. (1987) in a study which investigated slowly available N sources.

Further, statistical analysis revealed differences in recovery of applied N in clippings as a result of the different coating thicknesses, for AS, though differences among the urea treatments were limited to differences between the coated urea treatments and the uncoated urea treatment. No differences in N recovery were detected between the two coated urea treatments.

Recovery in stolons and roots. Recovery of applied N in the stolon and root system of bermudagrass receiving CAS-4.7 was highest, at 11%, followed by both coated urea treatments at 8%. Application of uncoated AS and urea resulted in a recovery of 7% and 6% of applied N in stolon and roots, respectively. The recovery of applied N in roots and stolons of bermudagrass receiving CAS-9.8 was lowest, at 5%.

Differences in recovery were also detected as a result of coating for the AS treatments. Statistical analysis revealed differences between CAS-4.7 and the other two AS treatments. However, there were no differences in recovery of applied N among the urea treatments as a result of coating.

Recovery in thatch and soil. Thatch played an important role in the fate of applied N in this lysimeter study. Recovery of applied N in thatch/soil (top 2.5 cm) was highest for lysimeters receiving uncoated N substrates. Analysis of

thatch in lysimeters receiving uncoated urea showed that 14% of the applied N was retained in the thatch layer, followed by 11% for uncoated AS at the end of the growing season. This suggests that relatively large quantities of N may be immobilized when large amounts of readily available N are applied to turfgrass. Recovery of applied N in thatch for lysimeters receiving the coated urea treatments was 11% as well. The coated AS treatments resulted in the lower recovery of N in the thatch layer, accounting for only 10% and 9% of the applied N.

The large amounts of fertilizer N immobilized in the top 2.5 cm suggest the presence of a large microbial biomass which acted as a sink for applied N. In addition this thatch/soil layer acted as a barrier, reducing leaching losses of applied N by prolonging the retention of N in this zone. It also appears that urea is more readily retained by the thatch layer than AS. This could be attributed to the increase in microbial activity as a result of an increase in pH resulting from urea hydrolysis. Overall, the thatch layer acted as an active zone which regulated the availability of applied N for plant uptake as well as N losses to the environment. These results are consistent with the findings of Starr and DeRoo (1981).

Starr and DeRoo (1981) conducted a study utilizing ^{15}N to determine the fate of applied N in a turfgrass system. They found that the thatch layer was highly suitable for an active

microbial population. Data collected in this study showed 36 to 47% of fertilizer N present in the soil-thatch pool.

Recovery in soil. Recovery of applied N in the top 2.5 to 15 cm of soil was low compared to the top 2.5 cm. Recovery ranged from 0.3% to 0.9% of applied N. This large difference between the recovery in thatch and soil further demonstrates the significance of N retention in the thatch layer.

Results and Discussion: 1993

Data collected during the bermudagrass growing season in 1993 gave results somewhat different from those obtained during the 1992 growing season. This could be attributed to the lower and less frequent rainfall amounts during the 1993 season. As a result, no leaching of applied N occurred. The impact of varying amounts of irrigation/rainfall was investigated by Morton et al. (1988). They found that limiting irrigation to meet evapotranspiration of the turfgrass significantly reduced, and in some cases eliminated, leaching of $\text{NO}_3\text{-N}$. These findings agree with the results obtained in 1993.

Bermudagrass growth and N uptake were higher in response to all treatments during this year because there was no leaching losses, resulting in an increased N supply available for plant uptake.

Growth of Bermudagrass

Bermudagrass growth during the second year of this lysimeter study is summarized in Table 5-8. Rainfall during

the second year of this study was drastically lower than that for the first year (Appendix). As a result, bermudagrass growth for 1993 was higher for all treatments compared to 1992. Uncoated AS and urea produced the highest growth during the second year of this study. This is most likely the result of longer residence time of applied N in the root zone for these uncoated N sources, due to lower rainfall amounts during the 1993 growing season.

Ammonium sulfate treatments. During the first 30 day after treatment application, differences in growth were observed between uncoated AS and the two coated AS treatments. However, no differences between the two coated materials were

Table 5-8. Growth of Tifway bermudagrass following N application (g lysimeter⁻¹).

Treatment	Monthly Growth at			Total Growth
	30d	60d	90d	
AS	40.2a ⁺	21.4a	15.2ab	76.8a
CAS-4.7	13.0b	18.5ab	18.9a	50.4b
CAS-9.8	13.2b	14.7b	13.4b	41.3b
Urea	32.0a	22.0b	15.7b	69.7a
CUrea-4.7	15.2b	34.8a	18.9b	68.9a
CUrea-10	14.4b	22.0b	26.9a	63.3a

+ Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

observed, with uncoated AS producing the highest growth. Bermudagrass receiving uncoated AS produced 52% of its total

growth during the first 30 days after application. Bermudagrass growth was three times higher in response to this uncoated substrate than for the other two coated materials. The coated AS treatments produced identical growth despite their different coating thicknesses. This suggests that both coated treatments were undergoing the induction period (period in which the coated materials imbibe water) of the release process during this initial stage of the 1993 experiment. Application of CAS-4.7 resulted in 26% of total bermudagrass growth during this 30 day period, while CAS-9.8 produced 36% of total seasonal bermudagrass growth.

During the second 30 days, differences between uncoated AS and CAS-9.8 were observed. No differences, however, were observed between CAS-4.7 and uncoated AS or CAS-9.8. Uncoated AS and CAS-4.7 produced the highest growth among the AS treatments. However, growth in response to the uncoated AS treatment diminished, with only 28% of total growth being produced during this period. Growth in response to CAS-4.7 increased concurrently with 37% of total bermudagrass growth being produced during this 30 day interval. Coated AS-9.8 again produced lower bermudagrass growth. However, 36% of the total seasonal bermudagrass growth for this treatment was produced during this time period.

During the last 30 days of the experiment, no differences in growth between uncoated AS and the two coated AS treatments were detected. Statistical analysis did reveal differences in

growth produced by CAS-4.7 and CAS-9.8. During this period, CAS-4.7 produced a greater growth followed by uncoated AS and CAS-9.8. Growth in response to uncoated AS was again lower, accounting for only 20% of total seasonal growth. However, CAS-4.7 again produced 37% of total bermudagrass growth during this period. Coated AS-9.8 also maintained a high growth rate during this period, with 32% of total seasonal growth produced.

Urea treatments. During the first 30 days after treatment application, differences in growth were observed between the uncoated treatment and the two coated urea treatments. Uncoated urea produced the highest growth during this time period. Lysimeters receiving uncoated urea produced 46% of their total growth during the first 30 days of the experiment, no differences among the two coated urea treatments were detected. Application of C Urea-4.8 resulted in 22% of total seasonal bermudagrass growth during this 30 day period. Coated Urea-10 produced 23% of total seasonal bermudagrass growth during this same period.

During the second 30 days, differences in growth between C Urea-4.8 and the other two urea treatments were observed, but not between uncoated urea and C Urea-10. Growth resulting from application of uncoated urea was reduced because of the depletion of this uncoated N source by the initial high N uptake. Therefore, uncoated urea only produced 32% of total seasonal growth during this period. Bermudagrass growth in

response to C Urea-10 was 35% of total growth during this period, while C Urea-4.8 produced the highest growth, with 51% of total seasonal bermudagrass growth being produced during this time.

During the final 30 day period of the bermudagrass growing season, differences between the C Urea-10 treatment and the other two urea treatments were observed. Coated Urea-10 produced the highest growth rate, though no differences were detected between uncoated urea and C Urea-4.8. Coated Urea-10 produced 42% of total bermudagrass growth, suggesting a continuous supply of N to the turfgrass. Uncoated urea and C Urea-4.8 only produced 20% and 27% of total bermudagrass growth, respectively, during this same period.

Nitrogen Uptake by Bermudagrass

Tifway bermudagrass N uptake was determined using the difference method. The N uptake pattern for bermudagrass was similar to that for growth. Both uncoated treatments and C Urea-4.7 produced the highest N uptake, followed by C Urea-10. Coated AS-9.8 produced the lowest overall N uptake.

Ammonium sulfate treatments. During the first 30 days after treatment application, differences in N uptake were observed between uncoated AS and the two coated AS treatments (Table 5-9). Uncoated AS produced the highest growth during this time period, with bermudagrass receiving uncoated AS accumulating 63% of its total N uptake during the first 30 days after treatment application. The high initial rate of N

Table 5-9. Nitrogen uptake by Tifway bermudagrass following N application (mg lysimeter⁻¹).

Treatment	NUP30 ⁺	NUP60	NUP90	Total
AS	1734a [*]	636a	396b	2766a
CAS-4.7	282b	509a	569a	1360b
CAS-9.8	268b	308b	335b	911c
CV ^{**}	8	21	16	11
Urea	1427a	643b	400c	2470a
CUrea-4.8	575b	1271a	595b	2441ab
CUrea-10	409b	666b	1007a	2082b
CV	13	16	15	10

⁺NUP30, NUP60 and NUP90=total monthly N-uptake at 30, 60 and 90 days;

^{*}Mean values within a treatment group and columns followed by the same letter are not significantly different according to LSD₀₅;

^{**}Coefficient of variation.

uptake is the result of the rapid availability of applied N in this substrate form, coupled with low rainfall. No differences between CAS-4.7 and CAS-9.8 were detected. Application of CAS-4.7 resulted in 21% of total bermudagrass N uptake during this 30 day period, while CAS-9.8 produced 29% of total seasonal bermudagrass N uptake.

During the second 30 days, differences in N uptake were observed between CAS-9.8 and the other two AS treatments, but no differences between uncoated AS and CAS-4.7 were detected. Uncoated AS and CAS-4.7 produced the highest N uptake by bermudagrass, with 23% and 37% of total N uptake produced during this period, respectively. This suggests an increase in N uptake in response to CAS-4.7 during this time period.

Coated AS-9.8 produced 34% of total bermudagrass N uptake during this 30 day interval.

During the last period of the experiment, differences in N uptake were detected between CAS-4.7 and the other two AS treatments. Coated AS-4.7 produced the highest N uptake, with 42% of uptake occurring during this time period. Uncoated AS and CAS-9.8 produced the lowest N uptake, accounting for 14% and 37% of total N uptake, respectively. This indicates that N uptake slowed considerably in response to uncoated AS, but increased for CAS-9.8. This is most likely the result of an increase in the N release rate with this coating during this time period.

Urea treatments. During the first 30 days after treatment application, differences in N uptake were observed between uncoated urea and the two coated urea treatments. No differences between the two coated urea treatments were observed, however uncoated urea produced the highest N uptake by bermudagrass. Bermudagrass receiving uncoated urea produced 58% of its total N uptake during the first 30 days of the experiment, while N uptake in response to uncoated urea was more than twice as much as that for the other treatments in this group. Coated Urea-4.8 produced 24% of total N uptake, followed by C Urea-10 with 20% of total N-uptake occurring during this same time interval.

During the second 30 days, differences in N uptake between C Urea-4.8 and the other two urea treatments were

observed, but no differences between uncoated urea and C Urea-10 were detected. Coated Urea-4.8 produced the highest N uptake in bermudagrass among the urea treatments, resulting in 52% of total N uptake. Nitrogen uptake in response to uncoated urea was 26% of total seasonal bermudagrass N uptake.

Coated Urea-10 produced 32% of total N uptake even though it was still lower than that for C Urea-4.8 during the same time period.

During the last 30 day period, differences in N uptake were detected among all of the urea treatments. Coated Urea-10 produced the highest N uptake during the last 30 day period, accounting for 48% of total N uptake during this time. Coated Urea-4.8 followed, producing 24% of total N uptake by bermudagrass. Uncoated urea produced the lowest N uptake, accounting for only 16% of the total N uptake. Nitrogen uptake data clearly showed the effect of coating N including different coating thicknesses on N uptake by bermudagrass.

Recovery of Residual ^{15}N Labeled N Applied in 1992

During the second year of the study, plant tissue, stolons and roots, thatch, and soil were analyzed for ^{15}N in order to quantify the status of N applied during 1992. Data analysis revealed that 10% to 22.4% of the applied ^{15}N labeled N was still present in the soil/turfgrass system (Table 5-10).

Recovery in clippings. Recovery of applied N in clippings varied according to N substrate and coating thickness. Nitrogen recovery was highest for bermudagrass receiving

Table 5-10. Percent recovery of applied ^{15}N -labeled N.

Treatment	Clippings	Stolons & Roots	Thatch & Soil	Soil A ⁺	Soil B ⁺
AS	1.8b [*]	0.7c	4.1b	1.5a	2.5b
CAS-4.7	4.7a	1.4b	5.3b	1.7a	3.5a
CAS-9.8	4.3a	2.7a	10.5a	1.9a	3.1ab
CV ⁺	20	25	22	37	20
Urea	1.8b	0.6b	5.1b	1.2a	2.2a
CU-4.8	2.5b	1.2a	6.1ab	1.1a	2.0b
CU-10	3.9a	1.5a	7.0a	1.5a	2.8a
CV	18	22	20	40	35

⁺Soil A=1.25 to 5.0 cm depth; ⁺Soil B=5.0 to 15 cm depth;

^{*}Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD_{05} ; ⁺Coefficient of variation.

heavily coated AS and urea, and lowest for uncoated AS and urea. Recovery of applied N in bermudagrass receiving CAS-9.8 was 4.3%, followed by 4% recovery for C Urea-10. The recovery of applied N in clippings for lysimeters receiving CAS-4.7 was 2.5%. Percent recovery of applied N was the same, 2.5%, in clippings from bermudagrass receiving the C Urea-4.8. Recovery for the uncoated materials was the same, at 1.8%.

Further, statistical analysis revealed differences in

recovery of applied N in clippings as a result of the different coating thicknesses. Differences in recovery between CAS-9.8 and the other two AS treatments were detected, with statistical analysis revealing the same differences among the Urea treatments.

Recovery in stolons and roots. Recovery of applied N in the stolon and root system of bermudagrass was highest, at 2.7%, in bermudagrass receiving CAS-9.8. Coated Urea-10, CAS-4.7 and C Urea-4.8 followed with recoveries of 1.5%, 1.4% and 1.2%, respectively. Recovery of ^{15}N labeled N in stolon and roots was lowest for bermudagrass receiving uncoated AS and urea, with only a 0.7% and 0.6% recovery, respectively.

Differences in recovery were detected among all three AS treatments. Recovery was highest for CAS-9.8, followed by CAS-4.7 and then uncoated AS. These data demonstrate the effects of coating and of coating thickness on residual N uptake approximately 15 months after application. However, in the case of the urea treatments, differences were only found between uncoated urea and the two coated urea treatments. Higher recoveries in stolon and roots were detected for the two coated treatments.

Recovery in thatch/soil. Recovery of applied N in thatch/soil (top 1.25 cm) was highest for lysimeters receiving CAS-9.8. Analysis of thatch in lysimeters receiving this treatment showed that 10.5% of the N applied in 1992 was retained in this layer. A recovery of 7% of the ^{15}N labeled N

was found in thatch from bermudagrass receiving C Urea-10. Coated Urea-4.8, CAS-4.7 and uncoated urea followed with N recoveries of 6%, 5.3% and 5.1%, respectively. The thatch layer for bermudagrass receiving uncoated AS retained the lowest ^{15}N labeled N, with a N recovery of only 4.1%.

Nitrogen recovery was twice as much for CAS-9.8 than for CAS-4.7 and uncoated AS. Differences among the urea treatments were detected in N recovery between C Urea-10 and uncoated urea. However, no differences were detected between C Urea-4.8 and the other two urea treatments.

Nitrogen recovery in the thatch/soil layer for 1993 revealed opposite results from those in 1992. Recovery of N in this layer was highest for lysimeters receiving uncoated AS and urea in 1992. However, 1993 data showed that N recovery was highest for lysimeters which received the coated treatments. This suggests that more N from uncoated treatments compared to coated treatments was immobilized during the first growing season in this layer, and later either released for plant uptake or lost to the environment.

Recovery in soil. Soil samples were taken to a depth of 15 cm and then sectioned from 1.25 cm to 5 cm and from 5 cm to 15 cm. Recovery data showed a higher concentration of applied N in the top 5 cm of soil compared to the 5 cm to 15 cm soil section, overall. Nitrogen recovery in the top 5 cm section ranged from 1% (C Urea-4.8) to 1.9% (CAS-9.8). Nitrogen recovery in the 5 cm to 15 cm section ranged from 2% (C Urea-

4.8) to 3.5% (CAS-4.7). The AS treatments had an overall higher N recovery in soil than the urea treatments, indicating higher retention of this ammoniacal N source in soil.

Summary and Conclusions

First year (1992)

Both uncoated AS and urea produced higher growth and N uptake during the first 30 days of the bermudagrass growing season. However, as the N supply was depleted through high initial uptake and through various losses, growth and uptake substantially decreased over time. After 56 days, growth of bermudagrass was minimal in response to these two uncoated N substrates, and N uptake was only half as much as that for the first 30 days. Bermudagrass growth and N uptake patterns were the same for both uncoated N substrates throughout the growing season.

Coating urea with two different coating thicknesses did not influence bermudagrass growth or N uptake differentially, though coating differences among the AS treatments did affect bermudagrass growth and N uptake. Coated AS-4.7 produced the highest growth, with a growth pattern similar to that of C Urea-10. Coated AS-9.8, however, produced the lowest growth throughout the bermudagrass growing season. Growth data suggested that the 9.8% coating on AS impedes the release of N and therefore results in lower growth.

Both coated urea treatments produced the highest N uptake among all of the treatments in this lysimeter study. Coated

AS-4.7 followed the coated urea treatments in N uptake, with a N uptake pattern similar to that of C Urea-10. Coated AS-9.8, however, produced the lowest growth throughout the bermudagrass growing season. The 9.8% coating on AS impeded the release of N and resulted in lower N uptake.

Coating the materials also affected leaching of $\text{NO}_3\text{-N}$ through the soil profile, by reducing leaching and lowering the concentration of $\text{NO}_3\text{-N}$ in the leachate. However, coating affected leaching differently, depending on the N substrate. Generally, higher $\text{NO}_3\text{-N}$ concentrations were detected in leachate for lysimeters receiving the urea treatments compared the to AS treatments. Higher release rates for the coated urea treatments resulted in higher $\text{NO}_3\text{-N}$ concentrations when compared to the coated AS treatments with the same coating thicknesses.

Overall recovery of applied N at the end of the 1992 growing season ranged from 27% to 72%, calculated using the ^{15}N method, with uncoated urea and AS having a similar N recovery. Nitrogen recovery for the coated treatments, however, varied. Coated AS-9.8 had the lowest recovery, apparently because its high coating thickness impeded release of the N substrate. However, C Urea-10 had the highest N recovery among all the treatments. This indicates that the same coating thickness on urea and AS results in different N release rates.

Second year (1993)

Lower and less frequent rainfall in 1993 resulted in no

N leaching and, consequently, higher growth and N uptake in general when compared to data collected in 1992. Because there was no leaching, uncoated urea and AS produced N uptake and growth which exceeded that of the coated treatments.

Recovery of residual ^{15}N labeled N ranged from 11% to 22%. More than half of the recovery was detected in the thatch/soil layer, suggesting the long-term retention of N in this layer. In addition, recovery in this layer was approximately half of that found for 1992. This suggest the remineralization of immobilized N in this layer, and subsequent release of the N for plant uptake.

CHAPTER 6
THE FATE OF APPLIED NITROGEN IN A USGA GOLF GREEN

Introduction

Establishing and maintaining a quality turfgrass in sand profiles requires elevated levels and frequent applications of N. Golf greens, in particular, present a challenge to efficient nutrient management. They require a high quality turfgrass with a short mowing height and, consequently, a shallow root system. Furthermore, golf greens require a high sand profile with a high infiltration rate for water management and playability. Thus, nutrient retention and plant uptake are hindered as a result of these factors.

Fertilizer technology has been utilized to increase uptake efficiency and reduce leaching potential under challenging conditions. The goal of an efficient nutrient management program is to optimize uptake and minimize environmental impact. Controlled-release and slow-release fertilizers (CRFs/SRFs) have been designed to increase nutrient retention and uptake by extending the duration of nutrient availability in the root zone while reducing the potential for leaching.

The objectives of this study were as follows: 1) to evaluate the growth and N uptake of bermudagrass in a USGA

golf green setting in response to polymer-coated N sources; 2) to investigate the effectiveness of polymer-coated N sources with different release rates in supplying N to turf and reducing leaching of applied N; 3) to quantify $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ leached through the USGA golf green profile.

Materials and Methods

A field lysimeter study was conducted at the University of Florida's G.C. Horn Field Turfgrass Laboratory in Gainesville, Florida, during the months of June, July and August in 1992 and 1993. Bermudagrass clippings, leachate samples and visual quality ratings were taken. Climatic data affecting growth and N movement through the profile were recorded throughout the study (APPENDIX).

Lysimeter Design and Construction

Thirty lysimeters were specially designed to meet the objectives of this study (Figure 6-1). PVC pipe, 15 cm in diameter, was cut to 46 cm length. A plastic woven mesh was affixed to the bottom of the pipe to allow percolate to flow through. A PVC cap, approximately 5 cm deep, was used to close the lysimeter and act as a water reservoir. Three holes were drilled in each lysimeter. The first hole was drilled at 20 cm from the top of the lysimeter, and a ceramic sampler connected to tygon tubing was placed horizontally below the root zone. The tubing was pulled through the hole, the hole was sealed with silicon caulking, and the tube was brought to the top of the lysimeter for sampling soil solution at this

depth. The second hole was drilled in the center of the cap at the bottom of the lysimeter. An adapter was placed into this hole and tygon tubing was attached. This tubing was also brought to the top of the lysimeter for sampling percolated water leached through the profile. The third hole was drilled directly above the cap. A polyethylene tube was inserted to serve as a ventilation channel and also to prevent suction during evacuation of the water reservoir.

USGA Golf Green Profile

The lysimeters were packed according to USGA golf green specifications. Each profile consisted of a 30 cm root zone-mix (Tables 6-1 & 6-2) overlying a 5 cm layer of coarse sand and a 10 cm layer of pea gravel. The root-zone mix consisted of a sand and peat mixture in the ratio of 85 to 15 (by volume) and was compacted to a bulk density of 1.4 g/cm^3 .

A field area of 2.5 m x 3 m was selected for lysimeter placement. Holes were dug to a depth sufficient for lysimeter installation. The surrounding area was left undisturbed. Packed lysimeters were placed in the field prior to sodding and were subsequently exposed both to rainfall and irrigation.

Turfgrass

"Tifgreen" bermudagrass (Cynodon dactylon) plugs, 15 cm in diameter, were washed free of soil and thatch and placed on the packed lysimeters. Bermudagrass was allowed to establish

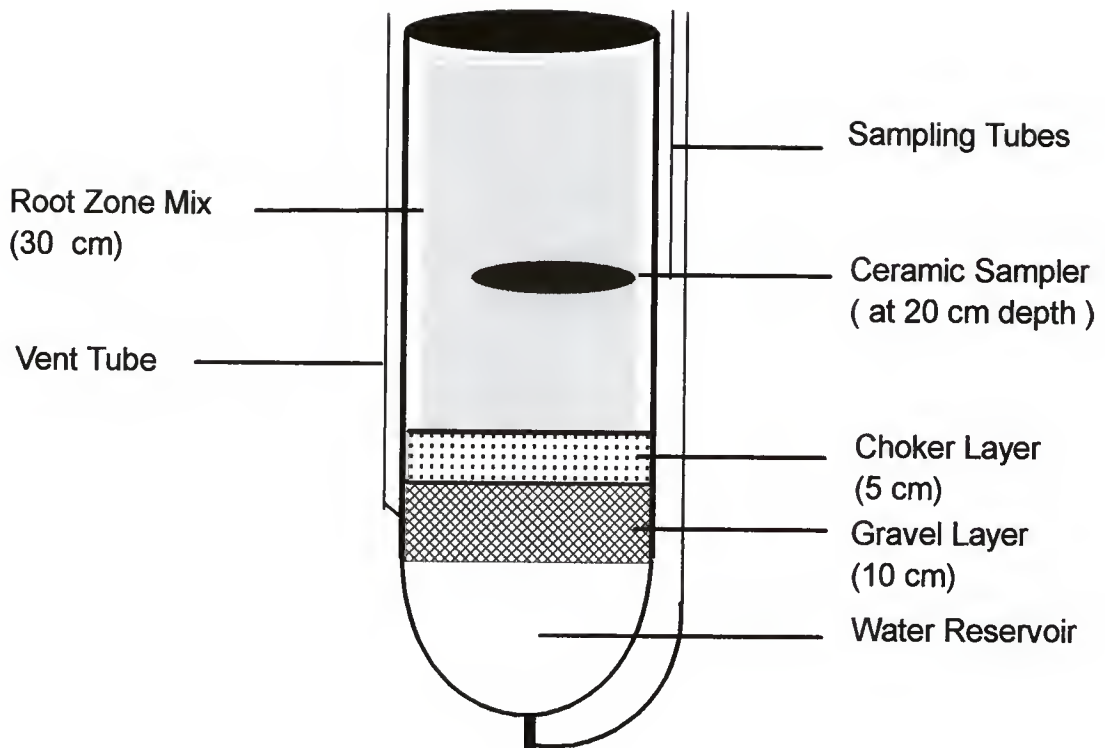


Figure 6-1. Closed-end lysimeter packed with a USGA golf green profile.

Table 6-1. Particle size analysis of Root-Zone Mix. (%)

Very Coarse	Coarse	Medium	Fine	Very Fine	Sand	Silt	Clay
4.8	18.0	49.6	25.2	1.2	97.6	1.9	0.5

Table 6-2. Physical properties of root-zone mix.

S.H.C.* cm/hr	Water Content at F.C.* (%) 0-15cm	Water Content at F.C. (%) 15-30cm	Bulk Density g/cm ³
38.6	8.7	12.9	1.4

*Saturated Hydraulic Conductivity.

*Field Capacity.

before fertilizer treatments were applied. The grass was clipped at 0.6 cm throughout the experiment, and irrigated to meet evapotranspiration rates of the bermudagrass.

Fertilizer Materials and Application Rates

This study consisted of 10 treatments including 3 N substrates with 3 levels of coating thickness and a control where N was not applied (Table 6-3). Fertilizer materials selected for this experiment consisted of uncoated and "micro-size" (-14+30 U.S. std. sieve size) polymer-coated $(\text{NH}_4)_2\text{SO}_4$ (AS), urea, and KNO_3 . All N treatments were applied at 1.5 kg N 100 m⁻², on May 21, June 19 and July 17 in 1992, and on May 27, June 29, and July 27 in 1993. All treatments were replicated three times in a randomized block design.

Additionally, $\text{Ca}(\text{NO}_3)_2$ was used in conjunction with the KNO_3 . The $\text{Ca}(\text{NO}_3)_2$ was necessary to complete the supply of the experimental rate of N application without exceeding the rate

of K application received in the other treatments. In addition to experimental N treatments, each lysimeter received phosphorus (P) in the form of concentrated super phosphate (CSP) at $0.25 \text{ kg P (100 m)}^{-2}$. Lysimeters receiving AS treatments received K in the form of KCl. Lysimeters receiving urea received K in the form of K_2SO_4 . Potassium was applied at $0.5 \text{ kg K (100 m)}^{-2}$. Additionally, sulfur (S) in the form of CaSO_4 was added to the lysimeters receiving urea and KNO_3 in order to balance S supply throughout the experimental units.

Sampling

During the experimental period for each year, all grass clippings were collected and dry weights were recorded. A total of 15 harvests were taken in 1992 and 12 in 1993. Plant tissue was analyzed for total N content (TKN) using a Rapid Flow Analyzer (RFA). Dry weight of grass clippings and N content of the plant tissue were used to quantify N uptake of applied N using the difference method. Using this method the apparent N uptake of applied N was estimated by subtracting N uptake in the turfgrass grown in the control lysimeters from the N uptake of treated lysimeters.

Leachate samples from depths of 20 cm and 46 cm were collected using a manifold connected to a vacuum pump. There were a total of 30 sampling events in 1992 and 18 in 1993. Samples were analyzed for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$.

Additionally, leachate samples from lysimeters receiving

urea were analyzed for urea. Data collected were used to quantify different forms of N leached through the golf green profile.

At the termination of the experiment each year, the bermudagrass was removed from each lysimeter and stolons and roots were collected. Root length and dry weight were recorded, with stolons and roots being analyzed for TKN. Statistical analysis of data was performed using Statistical Analysis System (SAS) procedures. The least significant difference (LSD) method was used for means separation.

Results and Discussion

1992

Growth of Bermudagrass

Tifgreen bermudagrass growth was affected differentially by N substrate and coating thickness of the applied N fertilizers. Total growth of the bermudagrass for each application, as well as the entire experimental period is summarized in Table 6-4. Coated AS-7.5 and C Urea-10.5 produced the highest growth among all treatments. Uncoated urea, on the other hand, produced the lowest growth. Coatings did not effect the overall growth within the AS and KNO_3 groups. Though coating did make a difference in overall growth among the urea treatments, no differences between the two coating thicknesses within this group were observed.

Growth was affected by several factors throughout the 90 day experimental period, including the available N pool,

Table 6-3 Nitrogen treatment specifications.

Treatment	% Coating	*Particle Size
AS	0	-14 + 30
CAS-7.5	7.5	-14 + 30
CAS-15	15	-14 + 30
Urea	0	-14 + 30
CUrea-10.5	10.5	-14 + 30
CUrea-21	21	-14 + 30
KNO ₃	0	-10 + 14
Ca(NO ₃) ₂	0	-12 + 30
CKNO ₃ -3	3	-10 + 14
Ca(NO ₃) ₂	0	-12 + 30
CKNO ₃ -6	6	-10 + 14
Ca(NO ₃) ₂	0	-12 + 30

* U.S. standard sieve size

growth cycle, temperature, and rainfall. The net effect of these factors during the experimental period rendered an overall result which differed when compared to growth produced during each treatment interval.

First treatment interval. During the first treatment interval (May 21st to June 15th), growth rates in response to treatments were lower than growth rates observed throughout the remaining experimental period. This is primarily the result of the growth cycle of bermudagrass, as well as the effect of temperature on release rates of coated N treatments. Bermudagrass is a warm season, C4 plant. Therefore, the optimum growth period for bermudagrass occurs during warm temperatures and extended hours of sunlight. In Florida, bermudagrass has its optimum growth rates beginning in early June and extending to mid August. Daily mean temperatures during the first treatment interval were generally lower (20 to 27 °C) than those recorded throughout the remainder of the experiment (APPENDIX).

Bermudagrass growth during the first treatment interval was highest in response to CAS-7.5 and C Urea-10.5, followed by C Urea-21 and uncoated AS and urea. The KNO_3 treatments produced lower growth, with CAS-15 producing the lowest growth during the first treatment interval. Both coating thickness and N substrate affected the growth of bermudagrass. The urea and AS treatments, which both supply an ammonical N (prior to

Table 6-4. Growth of Tifgreen Bermudagrass following each N application (gm lysimeter⁻¹).

Treatment	1 st Application	2 nd Application	3 rd Application	Total
AS	3.0ab*	4.6a	3.3b	10.9a
CAS-7.5	3.5a	5.2a	4.1a	12.9a
CAS-15	2.2b	4.8a	4.3a	11.2a
Urea	2.8a	3.4a	2.5b	8.7b
CUrea-10.5	3.5a	4.3a	4.1a	11.8a
CUrea-21	3.1a	4.5a	4.0a	11.5a
KNO ₃	2.4a	3.9a	2.9a	9.2a
CKNO ₃ -3	2.7a	4.5a	3.6a	10.8a
CKNO ₃ -6	2.6a	4.1a	3.8a	10.5a

*Mean values within a treatment group and columns followed by the same letter are not significantly different according to LSD₀₅.

nitrification), produced higher growth with the exception of CAS-15. Ammonical N is conducive to plant growth because it is less mobile and therefore remains in the root-zone longer, compared to N applied in the form of NO_3^- -N. The CAS-15 treatment failed to produce growth at a level corresponding with the other AS and urea treatments, because of its high coating thickness. The release of AS and urea from coated treatments is regulated by their solubility, coating thickness, and temperature. Solubility and temperature have a more profound effect on the release of AS from its polymer coating than for urea. Ammonium sulfate's solubility is lower compared to urea but increases as temperature increases, thus effecting its release. Therefore, CAS-15 failed to release sufficient N as a result of the lower temperatures which were experienced during the first treatment interval, subsequently producing the lowest growth during this period. The lower growth response to KNO_3 treatments during this period could be attributed to the low solubility of KNO_3 , which affects its release rate as well as its high mobility upon release.

During the first treatment interval, coating thickness had no effect on total growth of bermudagrass within each treatment group except for the AS treatments. Although differences in the effect of coating thickness were observed between the five harvests within the treatment interval, they were not sustained long enough to affect overall growth during this period. The heavily coated AS treatment (CAS-15) was the

exception. The percent coating, solubility of AS and low temperatures during this period combined to impede the release of adequate N for plant growth.

Second treatment interval. Growth increased for all treatments during the second treatment interval (June 19 to July 17). The increase in growth can be attributed to an increase in temperature and rainfall during this period, as well as closer approach to the peak growth period for bermudagrass. The highest growth was observed in response to CAS-7.5, and the lowest growth was observed in response to uncoated urea. Uncoated urea's performance during this treatment period can probably be attributed to increased mean temperatures (25 to 29°C) and rainfall and their effect on urea volatilization and leaching losses. The increase in temperature and rainfall also had a profound effect on the performance of CAS-15. During this period, CAS-15 produced the next to the highest growth, as compared to the lowest growth for the first treatment interval. Coating did not affect growth within individual treatment groups, with the exception of CAS-7.5 and uncoated urea.

Third treatment interval. Overall growth for the final treatment interval was lower when compared to the second treatment interval, but higher than for the first treatment interval. These results can be attributed to the lower temperatures and rainfall experienced, as well as the approaching end of the optimum growth period for bermudagrass.

The CAS-15 treatment, which had produced the lowest growth in the first treatment interval, produced the highest growth during this interval period. This further establishes the profound effect that temperature and rainfall (moisture) have on the release from this coated N substrate with 15% coating. The higher growth observed in response to CAS-15 could have also been influenced by the delayed release of residual N from the previous two applications. Uncoated urea again produced the lowest growth during this treatment interval.

Growth data revealed differences in coated and uncoated materials within the AS and urea treatment groups. However, no differences were found within the KNO₃ treatment group. There were no growth differences found among the different coating thicknesses within each group.

Stolons and Root Growth

Differences in root length were observed among treatments (Table 6-5). In general, the treatments that produced higher shoot growth had a shorter root length than treatments which produced lower shoot growth. This may be because roots grow longer when less competition (lower root density) is present. However, there was no treatment effect on root dry weight. Stolon dry weights, on the other hand, were highest for lysimeters receiving the AS treatments. Uncoated urea and KNO₃ produced the lowest stolon dry weights. These findings suggest that N supplied as AS remained in the root-zone longer and was taken up more readily than the other forms of N in

Table 6-5. Root length, and root and stolon dry weight (1992).

Treatment	Root Length (cm)	Root Wt. (g)	Stolon Wt. (g)
AS	17.4b*	1.96a	31.9a
CAS-7.5	16.1b	1.54a	25.5b
CAS-15	20.7a	1.64a	36.6a
Urea	17.8a	2.62a	13.5b
CUrea-10.5	16.5a	2.17a	24.4a
CUrea-21	17.8a	2.15a	16.4b
KNO ₃	18.2b	2.39a	13.9b
CKNO ₃ -3	21.2a	2.25a	18.5a
CKNO ₃ -6	21.6a	2.22a	18.4a

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

this lysimeter study. Furthermore, highly mobile uncoated urea and KNO₃ did not remain in the root-zone long enough to increase stolon biomass.

Nitrogen Concentration

Nitrogen concentration of the bermudagrass in response to treatments is summarized in Table 6-6. Nitrogen concentration was affected by N substrate, coating, and growth. Average N concentration over the 90 day experimental period was highest for CAS-7.5 and C Urea-10.5 and lowest for CAS-15 and uncoated KNO₃. Coating had an effect on overall % N in the bermudagrass. In general, the thin-coated materials within all three treatment groups had the highest % N in the bermudagrass grown on lysimeters receiving these treatments. This is a result of

Table 6-6. Average N concentration of Tifgreen bermudagrass following each N application.

Treatment	1 st Application	2 nd Application	3 rd Application	Avg
AS	3.4b*	3.4b	2.8b	3.2b
CAS-7.5	3.7a	3.9a	3.6a	3.7a
CAS-15	2.5c	3.0c	2.9b	2.8b
Urea	3.4a	3.1b	2.6b	3.0b
CUrea-10.5	3.6a	3.5a	3.1a	3.4a
CUrea-21	3.1b	3.1b	3.2a	3.1b
KNO ₃	3.2a	3.1a	2.4a	2.9a
CKNO ₃ -3	3.3a	3.4a	2.7a	3.1a
CKNO ₃ -6	3.1a	3.3a	2.8a	3.1a

*N1, N2, and N3=Average % N of 5 clippings for each treatment application interval; Avg %N=Average % N of all 15 harvests for all 3 treatment applications;

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

the more efficient release rate of these thinly-coated materials compared to the thickly-coated and uncoated treatments. Furthermore, smaller decreases in N concentration during each treatment interval were observed for coated materials compared to uncoated materials. This is an indication of the gradual release of N to the plant over longer periods of time.

Likewise, growth had an effect on N concentration throughout each treatment interval. Generally, higher growth rates corresponded to lower N levels in grass clippings. This is because of the dilution effect, where the grass produced a

larger biomass and thereby lower N concentrations.

Nitrogen Uptake

Nitrogen uptake pattern was closely related to that for growth (Table 6-7). Nitrogen uptake by Tifgreen bermudagrass was determined using the dry weight of grass clippings and N concentration of the plant tissue. The effect of the different N sources on N uptake was then quantified using the difference method.

Table 6-7. Nitrogen uptake by Tifgreen bermudagrass following each N application (mg N lysimeter⁻¹).

Treatment	1 st Application	2 nd Application	3 rd Application	Total
AS	65b*	134b	77b	276b
CAS-7.5	96a	198a	134a	428a
CAS-15	26c	139b	114a	279b
Urea	57b	78b	57b	192b
CUrea-10.5	89a	128a	114a	331a
CUrea-21	63b	127a	121a	310a
KNO ₃	43a	102a	46b	191a
CKNO ₃ -3	51a	130a	74b	255a
CKNO ₃ -6	43a	122a	84a	249a

*Mean values within a treatment and column group followed by the same letter are not significantly different according to LSD₀₅.

Nitrogen substrate and coating of applied N fertilizers affected total N uptake by Tifgreen bermudagrass during the 90 day experimental period. Nitrogen uptake data for all three treatment intervals rendered an overall pattern similar to

that of growth. Lysimeters receiving CAS-7.5 showed the highest N uptake followed by C Urea-10.5, C Urea-21, CAS-15, and uncoated AS. The KNO₃ treatments and uncoated urea produced lower N uptake by the bermudagrass.

The coated treatments produced a higher N uptake when compared with the uncoated materials. However, different coating thicknesses did not differ in their effect on total N uptake. This suggests that doubling the coating thickness among each coated N substrate did not produce the desired effect of extending N release and subsequently increasing N uptake. Furthermore, in some instances, N uptake was impeded by the slower release rate of the higher coating.

First treatment interval. During the first treatment interval (May 21st to June 15th), N uptake was lower than N uptake observed throughout the remaining experimental period. This is primarily the result of the annual growth cycle of bermudagrass, as well as the effect of temperature on release rates for the coated N treatments.

The N uptake by bermudagrass during the first treatment interval was highest in response to CAS-7.5 and C Urea-10.5, followed by uncoated AS, C Urea-21, uncoated urea, C KNO₃-3, C KNO₃-6, and uncoated KNO₃. The CAS-15 treatment produced the lowest N uptake. Both coating thickness and N substrate affected bermudagrass N uptake. Findings suggest that bermudagrass preferred NH₄⁺-N supplied in the form of AS compared to both urea and KNO₃. The CAS-15 treatment failed

to induce N uptake at a level corresponding with the other AS treatments. This is because higher temperature and rainfall was necessary for N release from this coating thickness. This is evidenced during the subsequent experimental period when temperature and rainfall had increased. Nitrogen uptake produced by the urea treatments was similar to that of the AS treatments, with the exception that C Urea-21 showed higher N uptake than CAS-15. The lower N uptake resulting from the KNO_3 treatments during this period could be attributed to the high mobility of this material.

During the first treatment interval, coating thickness affected N uptake for the AS and urea treatments, and differences were observed in all three AS treatments. The CAS-7.5 treatment produced the highest N uptake for the bermudagrass, followed by uncoated AS and CAS-15. The CAS-15 treatment produced the lowest N uptake as a result of its failure to release N rapidly enough to the plant. The thinly coated urea treatment produced higher N uptake than the other two urea treatments. The lower N uptake produced by uncoated urea was likely the result of a rainfall event which occurred the day after application, causing the leaching of this highly mobile uncoated material in the high sand profile. However, the thickly coated urea treatment produced the same level of N uptake as uncoated urea, because of its low release rate during this treatment interval. Finally, coated and uncoated KNO_3 did not affect N-uptake differently.

Second Treatment Interval. Nitrogen uptake was increased for all treatments during the second treatment interval (June 19 to July 17). This increase accounted for between 40% and 50% of the total N uptake recorded over the entire 90 days. The increase in N uptake can be attributed to an increase in temperature and rainfall, and subsequent increase in evapotranspiration, coupled with a peak in the growth cycle for bermudagrass. The highest N uptake was observed in response to CAS-7.5, and the lowest growth was observed in response to uncoated urea. Uncoated urea's performance during this treatment period can probably be attributed to increased mean temperatures (77 to 85°F) and rainfall with a resultant affect on urea volatilization and leaching losses. The increase in temperature and rainfall also had an effect on the performance of CAS-15. During this period, CAS-15 produced next to the highest N uptake as compared to the lowest N uptake during the first treatment interval. This directly mirrors CAS-15's effect on growth. Further statistical analysis of data for this period revealed that coating thickness among both the AS and urea treatments affected N uptake. The CAS-7.5 treatment produced a higher N uptake compared to CAS-15 and uncoated AS. Both coated materials in the urea group produced higher N uptake than uncoated urea. No differences were observed among the KNO_3 treatments.

With the exception of CAS-7.5 and uncoated urea, no differences in N uptake were observed. Nitrogen uptake

patterns during this treatment interval reflected those for growth during the same period.

Third treatment interval. Results for the final treatment interval showed that overall N uptake for this period was lower than that for the second treatment interval, but still higher than that for the first treatment interval. These results can be attributed to the lower temperatures and rainfall experienced as well as the approaching end of the optimum growth period for bermudagrass. Both the coated AS and urea treatments produced the highest N uptake during this treatment interval. The coated KNO_3 treatments had the same effect on N uptake as the uncoated AS and urea treatments. Uncoated KNO_3 produced the lowest N uptake during this period.

Nitrogen uptake data for this period revealed differences in coated and uncoated materials within all three treatment groups. In every case the coated materials out-performed the uncoated materials. There were no differences found among the different coating thicknesses within each group.

Nitrogen Uptake by Stolons and Roots

At termination of this experiment, stolons and roots for each lysimeter were analyzed for N, and N uptake was determined. A summary of these results is presented in Table 6-8.

Nitrogen uptake in the stolons was affected by N substrate and coating. The lysimeters receiving the AS and coated urea treatments showed higher N uptake in the stolon biomass than the other treatments. When N was supplied as

$\text{NH}_4^+\text{-N}$ a larger increase in biomass occurred probably as a result of an increase in N uptake. This is probably because less energy allocation is required, since no internal reduction of NO_3^-N is involved when the N is in the form of $\text{NH}_4^+\text{-N}$. This allows more energy to be allocated to plant growth. Furthermore, the initial immobilization of $\text{NH}_4^+\text{-N}$ resulted in a longer residence time within the root-zone and, therefore, allowed for later release of N and possible uptake by the plant. The KNO_3 treatments produced the lowest N uptake among all of the treatments. This can be attributed to its high leaching losses throughout the experimental period.

Table 6-8. Nitrogen uptake in stolons and roots ($\text{mg N lysimeter}^{-1}$).

Treatment	Root N Uptake	Stolon N Uptake
AS	5.4 a*	195.7a
CAS-7.5	3.2 b	124.9b
CAS-15	2.9 b	237.6a
Urea	14.5a	21.4c
CUrea-10.5	11.7a	183.8a
CUrea-21	6.7 b	91.2b
KNO_3	8.2a	5.9b
$\text{CKNO}_3\text{-3}$	5.7 a	59.8a
$\text{CKNO}_3\text{-6}$	7.0 a	82.4a

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD_{05} .

The uncoated treatments, with the exception of uncoated

AS, produced the lowest N uptake by stolons. These findings suggest that N supplied as AS remained in the root zone longer and was taken up more readily than the other forms of N in this lysimeter study. Furthermore, highly mobile uncoated urea and KNO_3 did not remain in the root zone long enough to increase stolon N uptake.

Visual Quality Ratings

Prolonging N release for plant uptake not only minimizes potential losses of N but also sustains more nearly uniform growth and an overall higher visual quality. Results from this study showed that coated materials sustained higher visual quality than uncoated treatments (Table 6-9). The coated urea and AS treatments produced the highest quality ratings, followed by the coated KNO_3 treatments. All three uncoated materials produced the lowest overall visual quality ratings, with the uncoated AS treatment producing the highest visual quality rating among the uncoated treatments. Although initial quality ratings for uncoated materials were high, quality ratings deteriorated at a faster rate after application for these materials than quality ratings for the coated materials.

Leaching of Applied N Fertilizer

A high-quality turfgrass on a putting green may require more N with higher frequency of application than a fairway turfgrass. This is the result of high infiltration rates in the high-sand profile of putting greens, as well as of the

Table 6-9. Visual quality rating of Tifgreen bermudagrass following each N application.

Treatment	1 st Application			2 nd Application			3 rd Application		
AS	a* 8.0	a 8.3	a 8.0	b 7.3	a 8.0	a 8.3	ab 6.7	ab 7.3	a 7.0
CAS-7.5	a 8.0	a 7.7	a 8.3	a 8.7	a 8.7	a 8.7	b 6.3	a 8.3	a 7.0
CAS-15	b 6.3	b 5.3	b 6.3	b 7.0	a 7.7	a 8.0	a 8.0	b 6.7	a 7.7
CV**	5	8	8	6	9	11	11	11	9
Urea	a 8.0	a 9.0	a 8.0	a 7.3	a 7.3	a 8.3	b 6.0	a 6.3	b 6.0
CUrea10	a 7.7	b 7.7	a 8.0	a 7.7	a 8.3	a 8.3	ab 6.7	a 7.3	a 7.7
CUrea21	b 6.7	c 7.0	a 7.7	a 7.3	a 7.3	a 7.7	a 7.3	a 8.0	a 7.7
CV	6	6	11	8	7	10	7	13	7
KNO ₃	a 7.7	a 6.7	a 6.0	a 6.0	a 5.7	a 7.3	a 6.7	a 7.7	a 7.7
CKNO ₃ -3	ab 6.7	a 6.3	a 6.0	a 6.0	a 6.3	a 7.7	a 6.3	a 7.7	a 6.3
CKNO ₃ -6	b 5.7	b 4.7	b 5.0	b 5.3	a 5.7	a 7.3	a 7.0	a 8.0	a 7.3
CV	9	10	10	6	10	8	11	7	11

*Mean values within a treatment and column group followed by the same letter are not significantly different according to LSD₀₅; ** CV=coefficient of variation.

shallow root system which is associated with low cutting heights. Therefore, nutrient management practices are needed to mitigate potential leaching in these kinds of turfgrass environments. Prolonging N residence time in the root zone can be achieved using controlled-release N sources. The concentrations of $\text{NO}_3\text{-N}$ leached to 20 cm and 46 cm were determined and are presented in Figures 6-2, 6-3, and 6-4. The maximum concentration of $\text{NO}_3\text{-N}$ detected at 46 cm depth was reduced as a result of increased coating thickness. The amount of N leached as $\text{NO}_3\text{-N}$ for each treatment interval and during the 90 day experimental period is summarized in Table 6-10. Results for each treatment group are discussed below.

Ammonium sulfate (AS) group. Nitrate concentrations at the 20 cm depth for AS were highest, at 20, 32 and 35 mg L^{-1} , during each treatment application interval, respectively (Fig.6-2). Nitrate concentrations for CAS-7.5 at the 20 cm depth was highest, at 3.5, 16, and 6 mg L^{-1} . The highest concentrations of $\text{NO}_3\text{-N}$ for CAS-15 at the 20 cm depth were 0.7, 1, and 0.8 mg L^{-1} . Maximum concentrations of $\text{NO}_3\text{-N}$ at this depth were detected five to seven days after application. This time period encompasses the initial time for nitrification to occur, followed by $\text{NO}_3\text{-N}$ travel time to the 20 cm depth. Based on the travel time to the same depth for N applied as $\text{KNO}_3\text{-N}$, nitrification of applied AS occurred within one to three days after application. This suggests a fast

nitrification rate for applied AS treatments during the experimental period.

Concentrations of $\text{NO}_3\text{-N}$ below the root zone at the 20 cm depth were higher than $\text{NO}_3\text{-N}$ values detected at the 46 cm depth. These former concentrations represent soil solution concentrations for $\text{NO}_3\text{-N}$ extracted from the unsaturated zone in the soil profile using a ceramic sampler. As the water percolated through the profile and into the water reservoir, the $\text{NO}_3\text{-N}$ concentrations became lower as a result of dilution between the two sampling depths. This dilution effect should be greater in a deeper profile as more water is required for leaching of $\text{NO}_3\text{-N}$.

Table 6-10. Nitrate leached to the 46 cm depth after each N application ($\text{mg N lysimeter}^{-1}$).

Treatment	1 st Application	2 nd Application	3 rd Application
AS	19.2a*	28.1b	22.8a
CAS-7.5	2.2b	48.4a	1.8b
CAS-15	2.1b	0.2c	0.1b
Urea	26.5a	37.7a	65.4a
CUrea-10.5	3.3b	10.0b	1.4b
CUrea-21	1.3b	1.8c	0.3b
KNO_3	132.8a	101.7a	131.0a
$\text{CKNO}_3\text{-3}$	97.4b	71.8b	97.8b
$\text{CKNO}_3\text{-6}$	66.2c	54.6c	75.4c

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD_{05} .

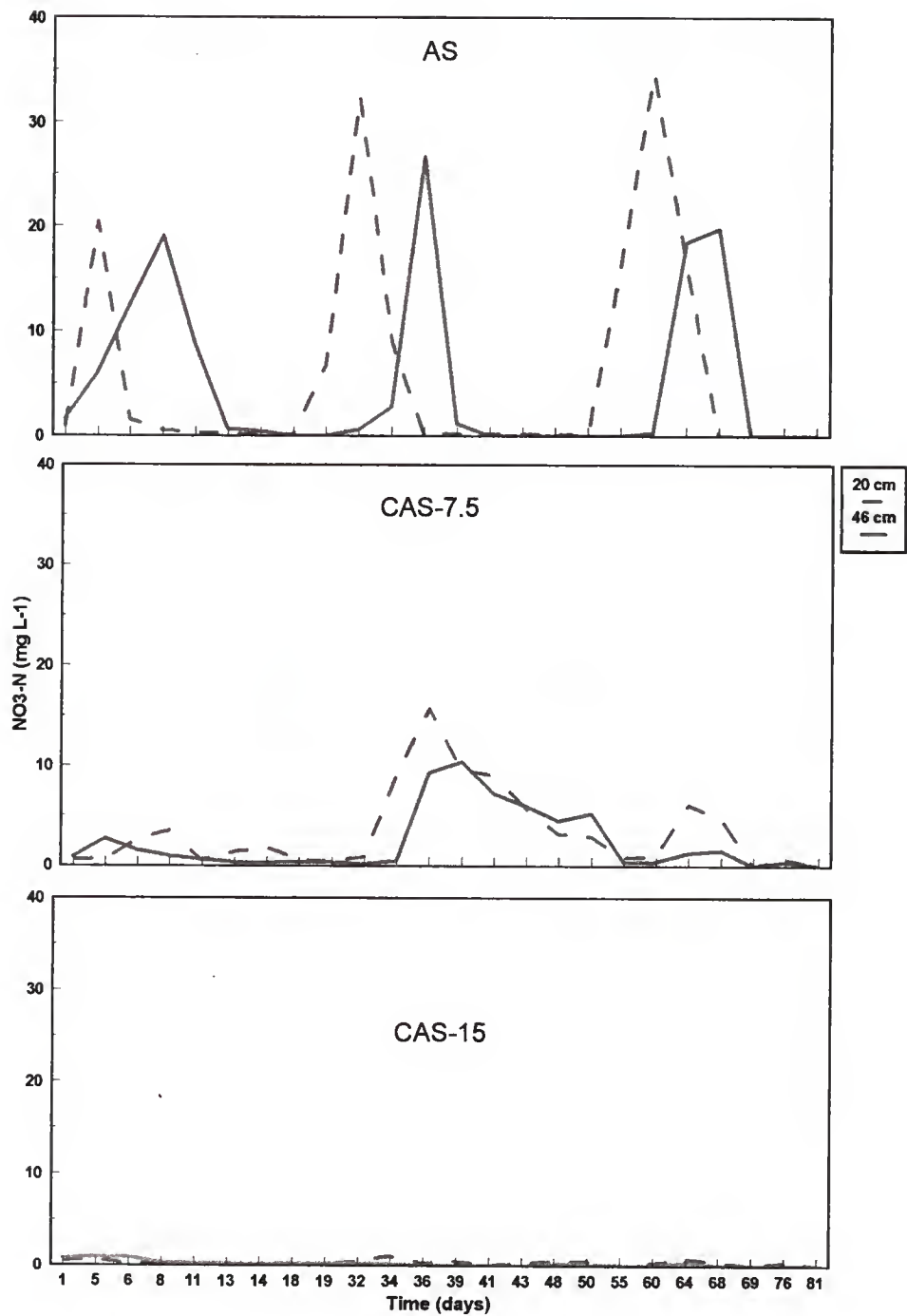


Figure 6-2. Concentrations of $\text{NO}_3\text{-N}$ at the 20 cm and 46 cm depths: AS treatment group.

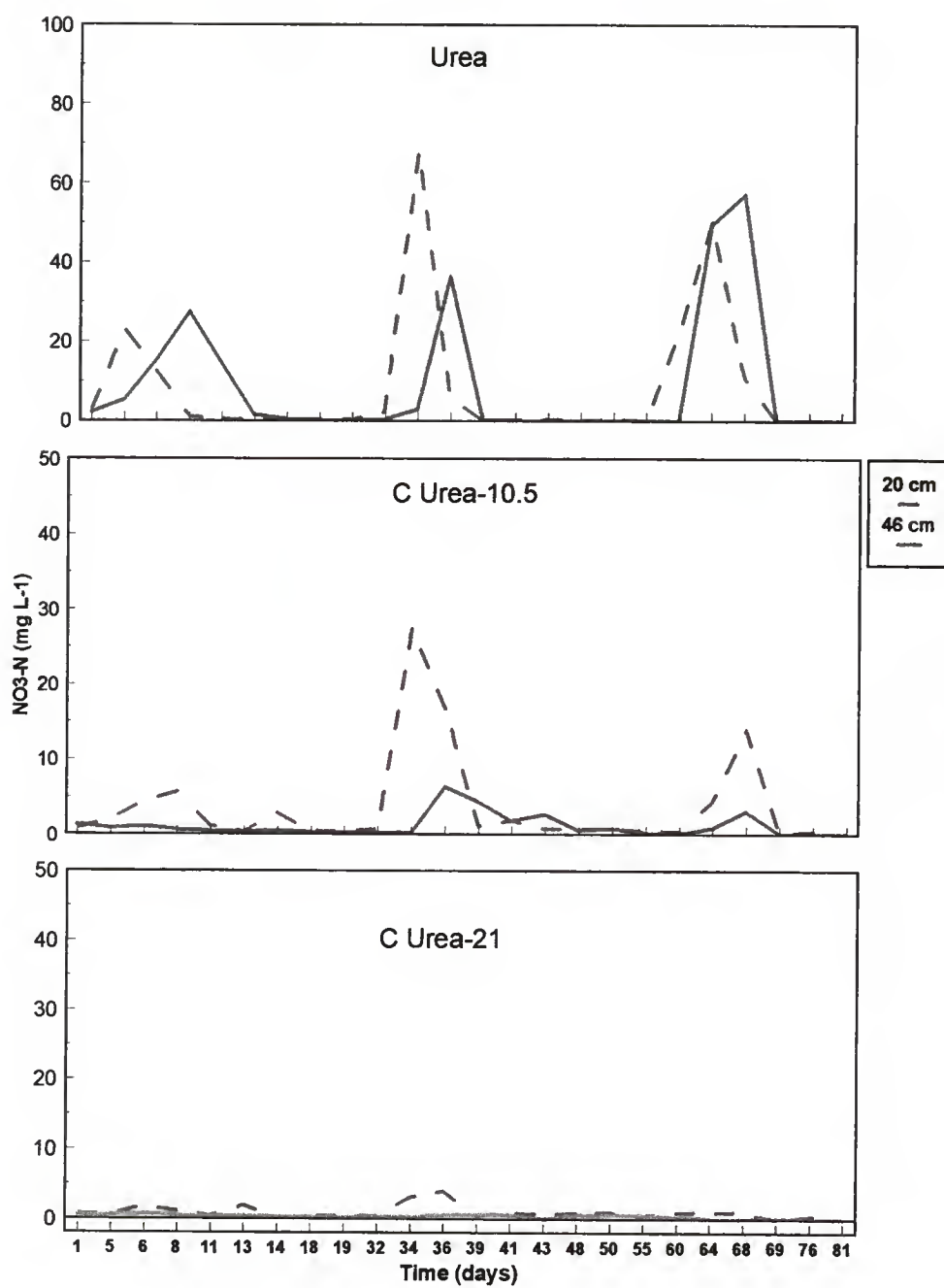


Figure 6-3. Concentrations of NO₃-N at the 20 cm and 46 cm depths: urea treatment group.

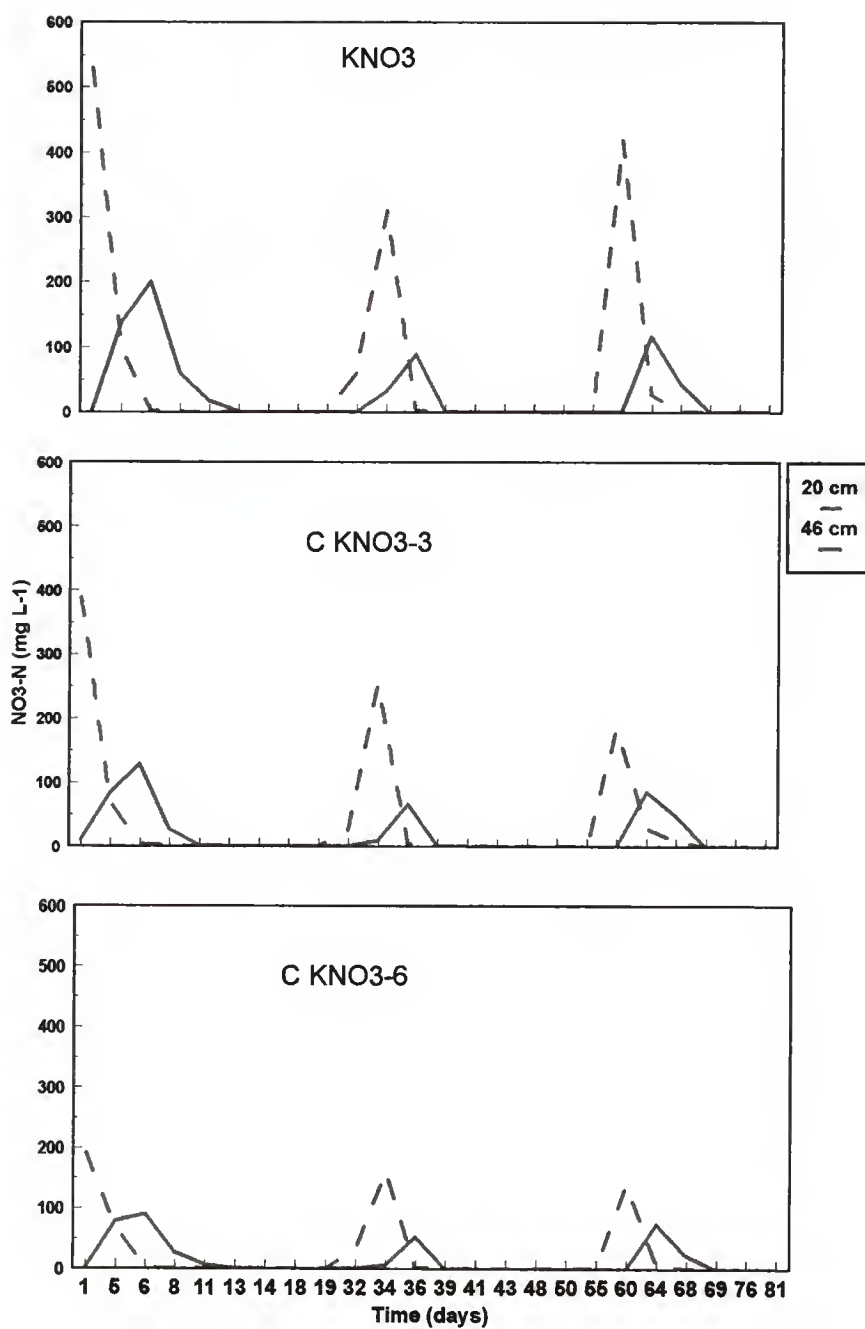


Figure 6-4. Concentrations of $\text{NO}_3\text{-N}$ at the 20 cm and 46 cm depths: KNO_3 treatment group.

Nitrate concentrations at the 46 cm depth were of particular interest in this study, because of the EPA drinking water standards and health concerns associated with concentrations of nitrate above $10 \text{ mg L}^{-1} \text{ NO}_3\text{-N}$. The highest levels of $\text{NO}_3\text{-N}$ for AS at the 46 cm depth were 19, 26.7, and 19.7 mg L^{-1} for each treatment interval, respectively. Maximum nitrate concentrations for CAS-7.5 were 2.6, 10.4, and 1.5 mg L^{-1} during the same time period, though the CAS-15 treatment never produced $\text{NO}_3\text{-N}$ concentrations above 1 mg L^{-1} . Maximum $\text{NO}_3\text{-N}$ concentrations at this depth were detected between seven and eight days after application. This clearly indicates the rapid movement of $\text{NO}_3\text{-N}$ once it leaches below the root zone. Coating AS lowered $\text{NO}_3\text{-N}$ concentrations at the 46 cm depth. Application of CAS-7.5 reduced the $\text{NO}_3\text{-N}$ concentration of leachate by 77% compared to values for uncoated AS. Application of CAS-15 resulted in a further reduction of $\text{NO}_3\text{-N}$ concentration of leachate to 99% when compared to uncoated AS.

The quantity of N leached through the profile was also affected by coating thickness. The percent of applied N lost through leaching varied between treatment intervals. During the first treatment interval, uncoated AS losses through leaching were 7.2% as $\text{NO}_3\text{-N}$ and 18.3% as $\text{NH}_4\text{-N}$. During the second treatment interval, leaching losses totaled 10.5% as $\text{NO}_3\text{-N}$ and 11.8% as $\text{NH}_4\text{-N}$. During the third treatment interval, leaching losses for uncoated AS were 8.5% as $\text{NO}_3\text{-N}$ and 5.5% as $\text{NH}_4\text{-N}$. Total N losses for all three treatment intervals

resulted in 70.1 mg of $\text{NO}_3\text{-N}$ and 95.0 mg of $\text{NH}_4\text{-N}$ leaching to the 46 cm depth, representing 20.1% of the total N applied over the 90 days. The CAS-7.5 treatment resulted in leaching losses of 0.8% as $\text{NO}_3\text{-N}$ during the first treatment interval, though no leaching of $\text{NH}_4\text{-N}$ occurred. During the second treatment interval, CAS-7.5 resulted in 18.1% leaching as $\text{NO}_3\text{-N}$ and 3.5% as $\text{NH}_4\text{-N}$. The third treatment interval resulted in leaching losses of only 0.7%, as $\text{NO}_3\text{-N}$. The total quantity of $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ leached from CAS-7.5 for all three treatment intervals was 52.4 mg as $\text{NO}_3\text{-N}$ and 9.5 mg as $\text{NH}_4\text{-N}$, representing 7.7% of the total N applied. The N leaching losses from CAS-15 were negligible during 90 day experimental period. Leaching losses for this treatment only accounted for 0.3% of the total N applied.

Urea group. Concentrations of $\text{NO}_3\text{-N}$ at the 20 cm depth for urea were highest, at 23, 68, and 50 mg L^{-1} for each treatment interval, respectively (Fig. 6-3). Maximum $\text{NO}_3\text{-N}$ concentrations for C Urea-10.5 during the three treatment intervals were 5.6, 27.4, and 14 mg L^{-1} , with the highest concentrations of $\text{NO}_3\text{-N}$ for C Urea-21 at this depth were 1.9, 3.9, and 0.9 mg L^{-1} , respectively. Maximum concentrations of $\text{NO}_3\text{-N}$ for the urea treatments were detected at the 20 cm depth at approximately the same time as those for the AS treatments, between five and eight days after application. This suggests rapid urea hydrolysis and a rapid rate of nitrification as well.

Nitrate concentrations detected at the 46 cm depth were generally lower than those detected at 20 cm. The highest levels of $\text{NO}_3\text{-N}$ for uncoated urea were 27.4, 36.5, and 57.2 mg L^{-1} . The application of C Urea-10.5 resulted in maximum $\text{NO}_3\text{-N}$ concentrations of 1.3, 6.3, and 3.0 mg L^{-1} during the three treatment intervals, respectively. The C Urea-21 treatment resulted in maximum $\text{NO}_3\text{-N}$ concentrations that were always less than 1 mg L^{-1} . Maximum $\text{NO}_3\text{-N}$ concentrations were detected at seven and eight days after application. This further establishes a travel time of one to three days for $\text{NO}_3\text{-N}$ to reach 46 cm once it is below the root zone at 20 cm under the experimental conditions. Coating urea lowered $\text{NO}_3\text{-N}$ concentrations substantially at the 46 cm depth. Application of C Urea-10.5 reduced $\text{NO}_3\text{-N}$ concentrations of the leachate by 87% compared to urea. Application of C Urea-21 resulted in a further reduction in $\text{NO}_3\text{-N}$ concentrations of the leachate by 99% compared to urea.

The quantity of $\text{NO}_3\text{-N}$ leached to the 46 cm depth from the urea treatments was also affected by coating thickness and varied between treatment intervals. Uncoated urea had losses of 9.2% as $\text{NO}_3\text{-N}$, 9.7% as $\text{NH}_4\text{-N}$, and 6.1% as urea during the first treatment interval. During the second treatment interval, uncoated urea resulted in leaching losses of 14.% as $\text{NO}_3\text{-N}$, 0.6% as $\text{NH}_4\text{-N}$, and 17.3% as urea, and losses of 24.5% as $\text{NO}_3\text{-N}$, 4.8% as $\text{NH}_4\text{-N}$ and 12.2% as urea during the third treatment interval. Total N losses for all three treatment

intervals accounted for 129.6 mg of $\text{NO}_3\text{-N}$, 40.5 mg of $\text{NH}_4\text{-N}$, and 95.4 mg of urea, representing 33.1% of the total N applied as uncoated urea. Leaching losses from C Urea-10.5 were 1.2%, 3.8% and 0.5% as $\text{NO}_3\text{-N}$ for the three treatment intervals, respectively. Urea-N and $\text{NH}_4\text{-N}$ were not detected in the leachate for the coated urea treatments, likely because the slow release rates of N from the coated materials may have resulted in such low concentrations of urea and $\text{NH}_4\text{-N}$ which were further diluted and therefore, became undetectable by the 46 cm depth. The total quantity of $\text{NO}_3\text{-N}$ leached from C Urea-10.5 for all three treatment intervals was 14.7 mg, representing 1.8% of the total N applied. The quantity of $\text{NO}_3\text{-N}$ leached from C Urea-21 was negligible for all three treatment intervals, accounting for only 0.4% of the total N applied over the 90 day experimental period.

Potassium nitrate (KNO_3) group. Concentrations of $\text{NO}_3\text{-N}$ at 20 cm depth for uncoated KNO_3 peaked at 532, 309, and 419 mg L^{-1} for each treatment interval, respectively (Fig. 6-4). Nitrate-N concentrations for $\text{CKNO}_3\text{-3}$ at this depth peaked at 391, 254, and 184 mg L^{-1} for the same treatment intervals, with peak concentrations of $\text{NO}_3\text{-N}$ for $\text{CKNO}_3\text{-6}$ detected at 194, 162, and 141 mg L^{-1} . Maximum concentrations for all three $\text{KNO}_3\text{-N}$ treatments were detected between three and five days at the 20 cm depth. The traveling time of $\text{NO}_3\text{-N}$ for this treatment group was faster than for the other treatments, as a result of the $\text{NO}_3\text{-N}$ form of this N substrate.

At the 46 cm depth the highest levels of $\text{NO}_3\text{-N}$ for uncoated KNO_3 were 201, 88, and 117 mg L^{-1} for each treatment interval, respectively. Maximum $\text{NO}_3\text{-N}$ concentrations for $\text{CKNO}_3\text{-3}$ were 129, 66, and 85 mg L^{-1} , respectively, while $\text{CKNO}_3\text{-6}$ produced the maximum $\text{NO}_3\text{-N}$ concentrations of 91, 53, and 74 mg L^{-1} at this depth. Application of $\text{CKNO}_3\text{-3}$ reduced $\text{NO}_3\text{-N}$ concentration of the leachate by 29.6% compared to uncoated KNO_3 , with application of $\text{CKNO}_3\text{-6}$ further reducing $\text{NO}_3\text{-N}$ concentrations by 48.1% compared to uncoated KNO_3 . Coating these treatments did not have as significant an effect on reducing the concentrations of $\text{NO}_3\text{-N}$ leached to the 46 cm depth because of the concurrent application of uncoated $\text{Ca}(\text{NO}_3)_2$ with each KNO_3 treatment. Additionally, the coating thicknesses for the two coated KNO_3 treatments were substantially lower than for the other coated materials used in this experiment, therefore resulting in higher concentrations of $\text{NO}_3\text{-N}$ being released.

The quantity of $\text{NO}_3\text{-N}$ leached from the KNO_3 treatments was much greater than that leached from the other treatment groups. The quantity of $\text{NO}_3\text{-N}$ leached to the 46 cm depth from uncoated KNO_3 was determined to be 49.7%, 38%, and 49% of the amount of N applied for each treatment interval, respectively. The total quantity of $\text{NO}_3\text{-N}$ leached from uncoated KNO_3 for all three treatment intervals was 366 mg, representing 45.6% of the total N applied during the 90 day period. The quantity of $\text{NO}_3\text{-N}$ leached from $\text{CKNO}_3\text{-3}$ totaled 36.4%, 26.8%, and 36.6% of

the N applied during each treatment interval. This resulted in 267 mg of $\text{NO}_3\text{-N}$ leached during the entire experimental period, equaling 33.3% of the applied N. The quantity of $\text{NO}_3\text{-N}$ leached from $\text{CKNO}_3\text{-6}$ was lowest, at 24.8%, 20.4%, and 28.2% of N applied for each treatment interval. These percentages represent 196 mg of $\text{NO}_3\text{-N}$ leached to 46 cm over the 90 day period, or 24.5% of the total N applied. Coating KNO_3 reduced the quantity of $\text{NO}_3\text{-N}$ leached.

These results suggest that when uncoated $\text{NO}_3\text{-N}$ is applied to sand based golf greens, the potential for N leaching is high. In a study conducted by Gaines and Gaines (1994), the importance of soil texture on leaching of $\text{NO}_3\text{-N}$ was investigated. They found higher $\text{NO}_3\text{-N}$ concentrations leached through sand and greensmix (85% sand:15% peat) than loamy sand and sandy clay loam. Their data showed no differences in $\text{NO}_3\text{-N}$ leaching through sand when compared to greensmix. Similar results were obtained in another study conducted by Brown et al. (1982) comparing percent $\text{NO}_3\text{-N}$ leached through different soil textures.

Nitrogen Transformations

The primary path of loss of applied N was through leaching. However, microbially mediated processes such as immobilization, nitrification and denitrification, as well as enzymatic hydrolysis of urea and subsequent NH_3 volatilization, may have also played a role in the total loss of N, and also in the form and quantity of N lost through leaching.

These processes could not be quantified as to their relative contribution to total loss of applied N. However, the analysis of leachate samples did provide some information regarding N transformation characteristics of the applied N.

Leachate samples collected at the 20 cm depth during the first treatment interval from lysimeters that received uncoated urea showed that urea hydrolysis and subsequent nitrification of $\text{NH}_4\text{-N}$ occurred within the first six days (Figure 6-5). In fact, urea from the uncoated urea treatment was detected at its highest concentration one day after treatment application at this depth. By the sixth day after treatment application, no urea was detected. The highest concentrations of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ detected were at five and six days after application, respectively. Comparing these data to data collected for lysimeters receiving uncoated AS, it appears that nitrification was not only faster when uncoated urea was applied but also resulted in more $\text{NO}_3\text{-N}$ being leached. This can be explained by an increase in pH to an optimum range for this microbially mediated process. The increase in pH is a result of the hydrolysis of urea.

Total Recovery of Applied Fertilizer N

Recovery of applied N in plants has been reported in numerous studies. Ranges for N uptake by plants vary from 25% to 65%. The wide range in N use efficiency by plants is the result of numerous factors. Recovery rates of applied N in the bermudagrass varied according to N substrate, coating

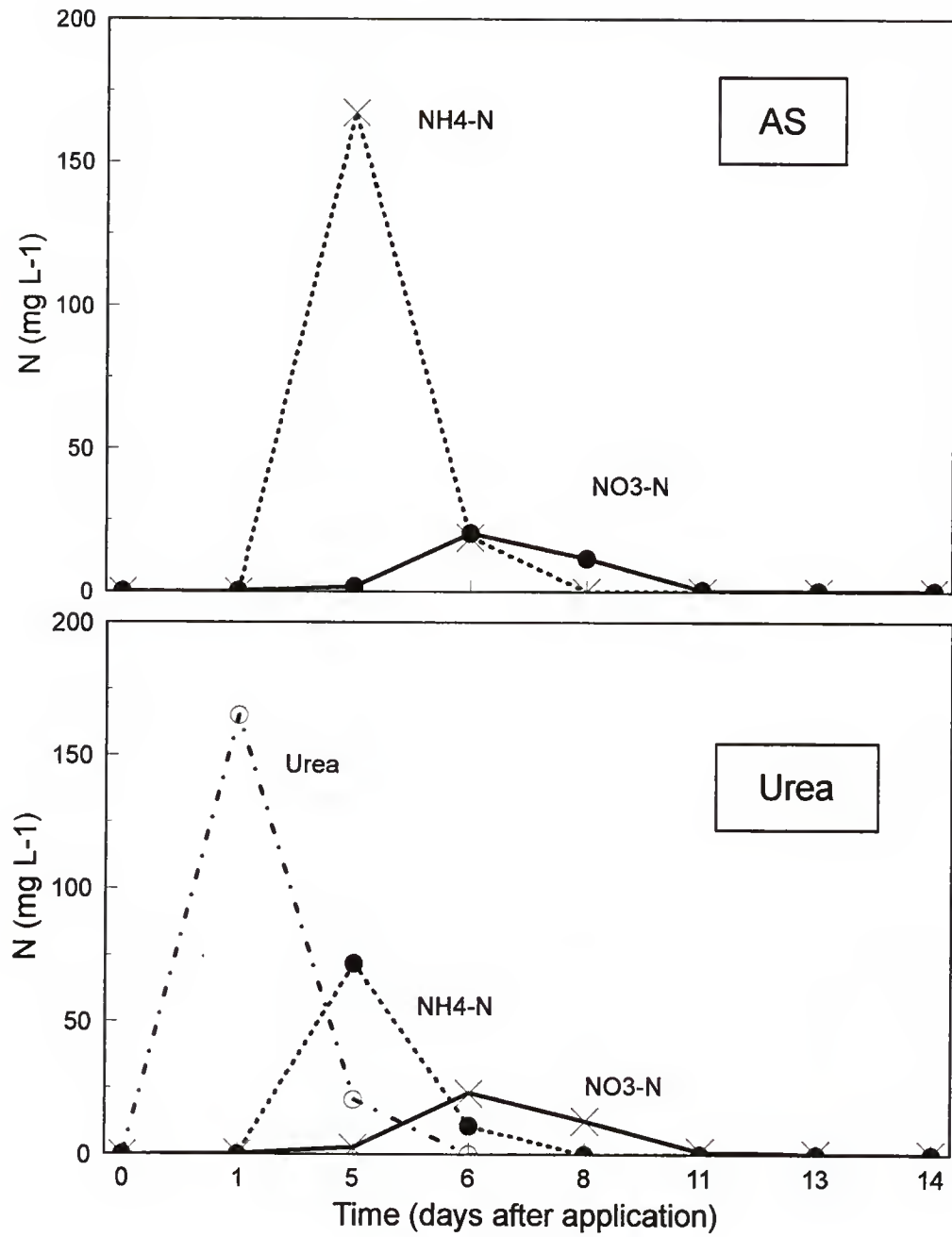


Figure 6-5. Nitrogen transformations of applied AS and Urea.

thicknesses, and time of application. Nitrogen uptake recovery encompasses N recovered in clippings, stolons and roots. Nitrogen uptake ranged from 25.5% for uncoated KNO_3 to 69.4% for CAS-7.5 (Fig. 6-6 to 6-8).

Overall percent N recovery by bermudagrass was highest for the coated materials. However, the treatments with the thickest coating produced a lower recovery of N in the plant compared to their thinly coated counter parts, with the exception of CKNO_3 -6. This is probably the result of the slower release of N when the coating weight was increased. Nitrogen substrate also had a major impact on percent N recovery by the bermudagrass. The AS treatments produced the highest percent recovery in the plant, followed by the urea treatments. The KNO_3 treatments produced the lowest overall percent recovery. The percent recovery by bermudagrass receiving uncoated urea and KNO_3 was lower than that for bermudagrass receiving uncoated AS. These data suggest preferential uptake of NH_4 -N over the NO_3 -N. Furthermore, this may be a reflection of the lower leaching fraction in the uncoated AS treatment when compared to the other uncoated treatments.

Recovery of N in leachate varied from 45.5% for uncoated KNO_3 to less than 1% for CAS-15 and C Urea-21. Recovery of N in the leachate included urea-N, NH_4 -N, and NO_3 -N. However, N recovered in the form of urea-N was only detected in leachate samples collected from lysimeters receiving uncoated urea, and recovery of NH_4 -N was limited to lysimeters receiv-

ing uncoated AS and uncoated urea. Data clearly showed that the differences in N recovery in the leachate were the result of coating presence and coating thicknesses. Nitrogen uptake to leaching loss ratios were determined for each treatment (Table 6-11). These ratios reflect the impact that coating had on both N uptake and N in leachate collected at the 46 cm depth. These ratios clearly reflect the drastic decreases in leaching losses as a result of coating and coating thicknesses within each treatment group. High ratios are indicative of low leaching potential.

Table 6-11. Ratio of N uptake to N leached.

Treatment	N Uptake (mg)	N Leached (mg)	N Uptake: N Leached
AS	477b*	165a	2.9
CAS-7.5	556a	62b	9.0
CAS-15	520ab	2.3c	226
Urea	228c	265a	0.9
CUrea-10.5	527a	14.7b	36
CUrea-21	408b	3.1b	130
KNO ₃	205b	366a	0.6
CKNO ₃ -3	321a	267b	1.2
CKNO ₃ -6	338a	196c	1.7

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

Total recovery of applied N fertilizer varied according to N substrate and coating thickness (Figures 6-6, 6-7, and 6-8). The thickly coated treatments had a lower recovery within

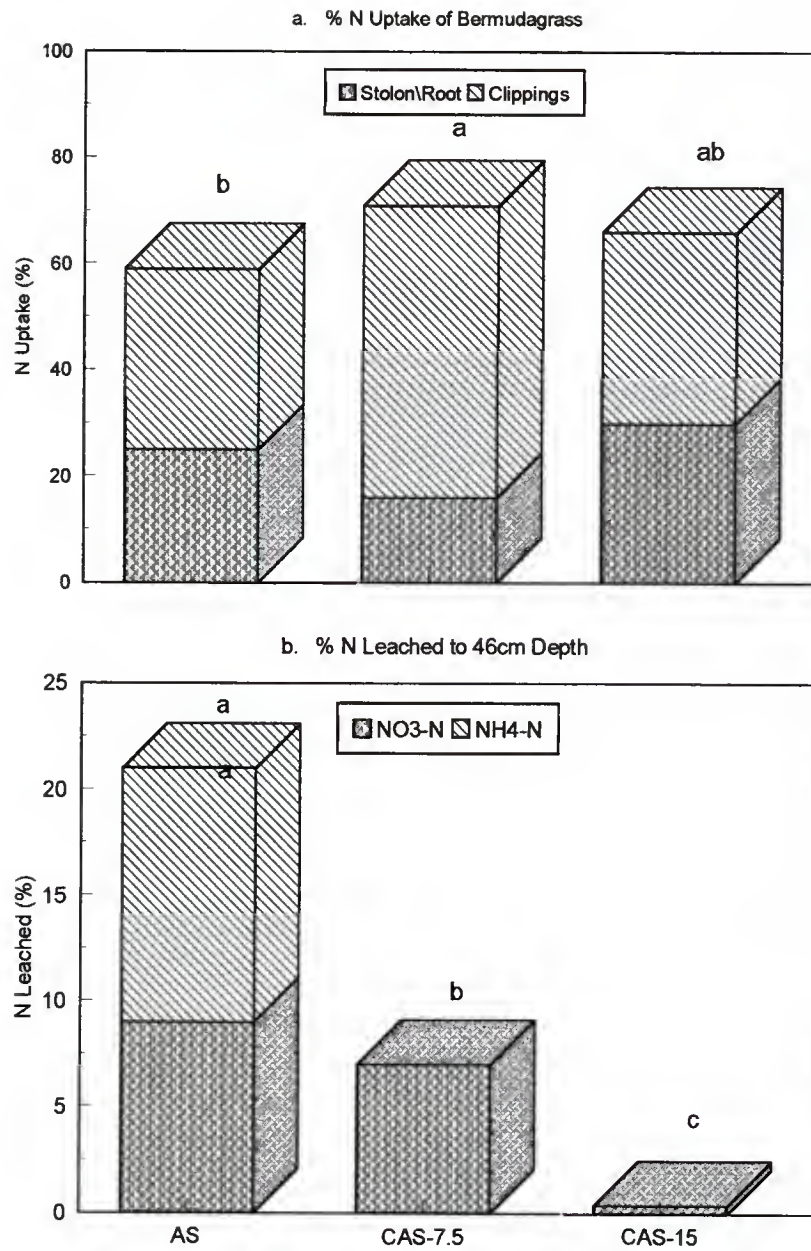


Figure 6-6. Nitrogen uptake and leaching recovery (1992): AS treatment group.

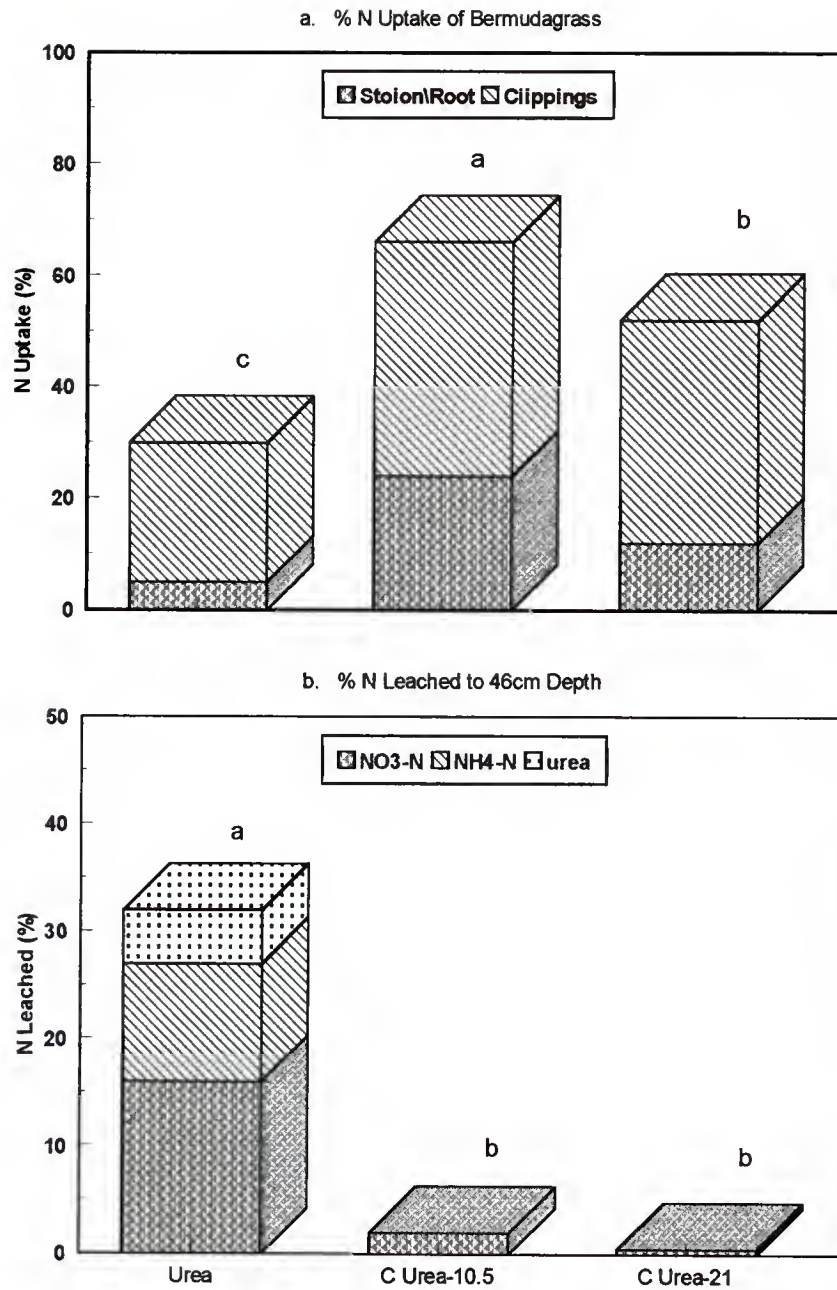


Figure 6-7. Nitrogen uptake and leaching recovery (1992): urea treatment group.

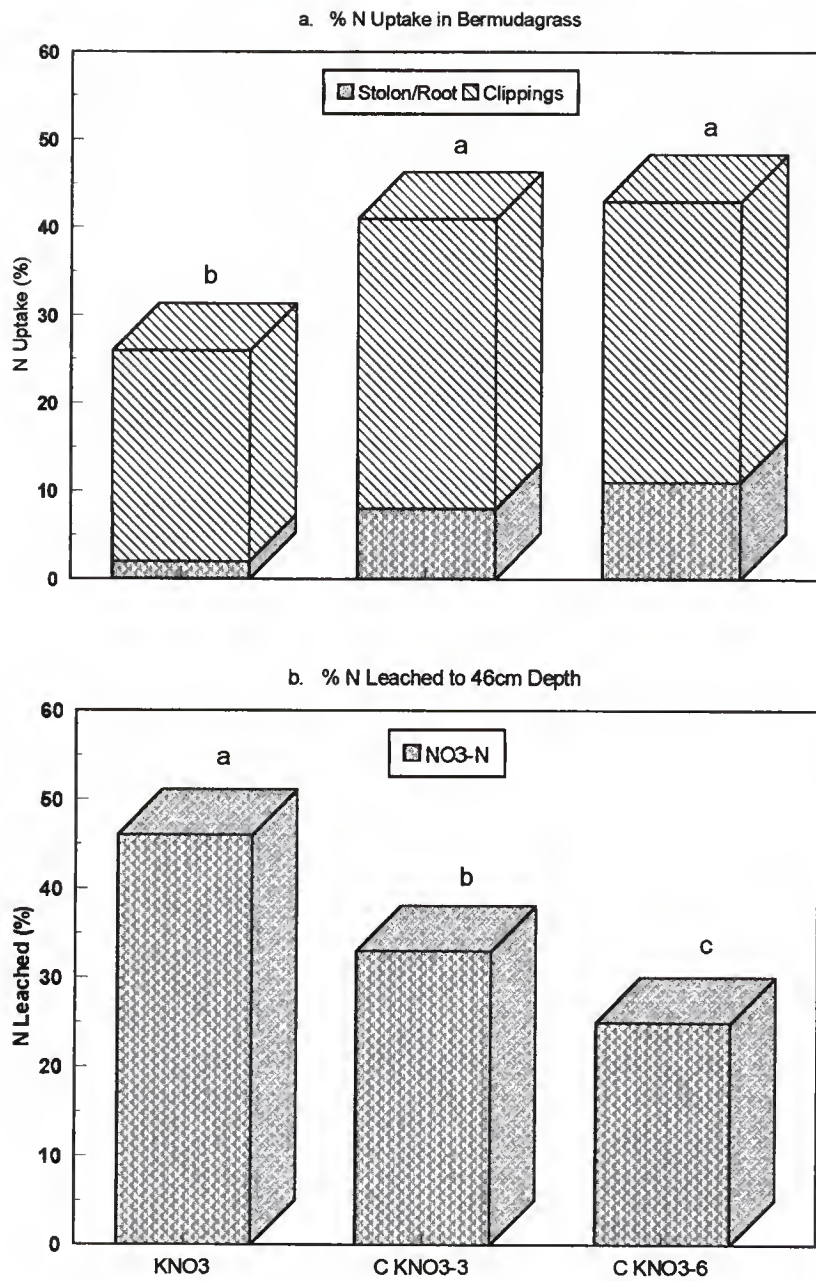


Figure 6-8. Nitrogen uptake and leaching recovery (1992): KNO_3 treatment group.

each treatment group. This lower recovery could be attributed to failure of the coating to release all of the available N during the experimental period, along with gaseous losses which could not be accounted for. Uncoated materials had an over all higher total recovery rate than coated materials, with the exception of uncoated urea. This is either because uncoated materials moved through the golf green profile quickly or were taken up by the plant. The experimental design allowed for quantification of the rapid downward movement of N. Furthermore, availability of the N was immediate and not dependent on the release rates associated with coating. Uncoated urea failed to produce a recovery commiserate with that of the other uncoated materials, due to potential losses as a result of NH_3 volatilization.

Results and Discussion

1993

Growth of bermudagrass

Bermudagrass growth in the second year had a similar growth pattern to that of the first year, and was similarly affected by N-substrate and coating thickness of applied N. Total growth of bermudagrass for each application period, as well as the entire experimental period is summarized in Table 6-12.

Overall growth data indicated that CAS-7.5 and uncoated AS produced the highest growth among all treatments, while

coated KNO_3 -6 produced the lowest growth. Coating affected overall growth within both the AS and urea treatment groups.

Table 6-12. Growth of Tifgreen bermudagrass following each N application (gm lysimeter^{-1}).

Treatment	1 st Application	2 nd Application	3 rd Application
AS	3.60a	5.64a	4.01a
CAS-7.5	3.57a	5.96a	4.00a
CAS-15	1.41b	3.87b	4.06a
Urea	3.44a	4.79a	2.55a
CUrea-10.5	2.97a	4.99a	3.13a
CUrea-21	2.48b	4.20a	3.25a
KNO_3	2.00a	3.17a	3.69a
CKNO_3 -3	1.58ab	3.49a	3.18a
CKNO_3 -6	1.05b	3.25a	3.48a

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD_{05} .

However, no coating affect was observed for bermudagrass receiving the KNO_3 treatments.

First Treatment Interval. During the first treatment interval (May 27 through June 25), the growth rates in response to treatments were lower than growth rates observed throughout the remaining experimental period. This is similar to growth data collected during the first year of the experiment, and is primarily the result of the annual growth cycle of bermudagrass along with the lower temperatures and rainfall

experienced during this time period as discussed in the section on growth during 1992.

Bermudagrass growth during the first treatment interval was highest in response to uncoated AS and CAS-7.5, followed by uncoated urea and the coated urea treatments. The KNO_3 treatments produced the lowest growth, with CKNO_3 -6 producing the lowest growth during the first treatment interval. The uncoated treatments produced higher growth during the first treatment interval when compared with growth produced by these treatments during the same time period in 1992. One explanation for these differences is the lower rainfall experienced in 1993, resulting in lower leaching of these uncoated materials.

During the first treatment interval, coating thickness had an effect on growth produced in response to the AS treatments. Statistical analysis also revealed differences between uncoated AS and CAS-15, and between CAS-7.5 and CAS-15. No differences in growth as a result of coating thickness were detected among the urea and KNO_3 treatment groups.

Second Treatment Interval. Growth in response to all treatments was increased during the second treatment interval (June 29 through July 20). The increase in growth during this time interval can again be attributed to the increase in temperature and rainfall. The highest growth rate was observed in response to CAS-7.5, followed by uncoated AS, C Urea-10.5, uncoated urea, C Urea-21 and CAS-15, respectively.

The KNO₃ group again produced the lowest growth. Further statistical analysis of the data revealed that coating had no affect on growth, with the exception of the AS treatment group.

Third Treatment Interval. Growth was higher during the third treatment interval (July 27 through August 25) when compared to the first treatment interval. However, it was generally lower than for the second treatment interval. This is an indication of the approaching end of the optimum growth period of bermudagrass, as well as of lower temperatures during this period when compared to the second treatment interval. The AS treatment group produced the highest growth during this period, with growth in response to CAS-15 increasing significantly over time and resulting in the highest growth among all treatments for the last treatment interval. However, there were no differences in growth as a result of coating for this treatment group. The KNO₃ treatment group followed the AS treatment group with respect to bermudagrass growth. The urea treatments produced the lowest growth during this time period, with uncoated urea producing the lowest growth overall.

Growth data revealed an overall pattern similar to that for growth in 1992. However, with the exception of the KNO₃ treatments, growth was higher overall for the uncoated treatments in 1993. This can be attributed to the lower rainfall experienced during the 1993 growing season.

Nitrogen Uptake

Nitrogen uptake was closely related to growth. Nitrogen substrate and coating of applied N fertilizers affected total N uptake by Tifgreen bermudagrass during the 90 day experimental period. Total N uptake by the bermudagrass for each application period as well as the entire experimental period is summarized in Table 6-13. Nitrogen uptake data for the total of the three treatment intervals rendered an overall pattern similar to that of growth. Lysimeters receiving CAS-7.5 showed the highest N uptake, followed by uncoated AS, C Urea-10.5, uncoated urea, C Urea-21 and uncoated KNO_3 . The coated KNO_3 treatments and CAS-15 produced lower uptake of N by the bermudagrass.

Statistical analysis revealed differences in N uptake in response to the heavily coated treatments when they were compared with the uncoated and thinly coated treatments in all three treatment groups. These data suggest that N uptake was reduced by the lower rainfall experienced during this growing season and the slower release rate of N from the treatments with higher coatings.

First Treatment Interval. During the first treatment interval (May 27th to June 25th), N uptake in response to treatments was lower than N uptake observed throughout the remaining experimental period with the exception of uncoated AS and urea. This is primarily a result of the growth cycle of bermudagrass as well as the effect of temperature on

Table 6-13. Nitrogen uptake by Tifgreen bermudagrass following each N application (mg N lysimeter⁻¹).

Treatment	1 st Application	2 nd Application	3 rd Application	Total
AS	143a*	134ab	153a	430a
CAS-7.5	119a	168a	159a	446a
CAS-15	30b	102b	132a	264b
Urea	135a	119a	76b	330ab
CUrea-10.5	108a	141a	130a	379a
CUrea-21	69b	112a	116a	297b
KNO ₃	53a	74a	158a	285a
CKNO ₃ -3	38b	87a	130a	255a
CKNO ₃ -6	18c	85a	141a	244a

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

release rates of coated N materials.

Nitrogen uptake by bermudagrass during the first treatment interval was highest in response to uncoated AS and urea, followed by CAS-7.5, C Urea-10.5, C Urea-21, uncoated KNO₃, CAS-15, C KNO₃-3 and C KNO₃-6, in that order. Both coating thickness and N substrate affected the N uptake by bermudagrass.

During the first treatment interval, coating thickness affected N uptake for all three treatment groups. Differences between CAS-15 and the other two AS treatments were observed. The CAS-7.5 treatment produced the highest N uptake by the bermudagrass, followed by uncoated AS and CAS-15. The CAS-15 treatment produced the lowest N uptake as a result of its

failure to release sufficient N for the plant. The thinly coated urea treatment produced higher N uptake than the other two urea treatments. However uncoated and thinly coated urea did not affect the N uptake differently. Thickly coated urea produced the lowest N uptake among this treatment group. Finally, statistical analysis revealed differences between all of the KNO_3 treatments, with uncoated KNO_3 producing the highest N uptake followed by CKNO_3 -3 and CKNO_3 -6, respectively.

Second Treatment Interval. Nitrogen uptake was increased by the heavily coated treatments in each treatment group during the second treatment interval (June 29 to July 20). The increase in N uptake can be attributed to an increase in temperature and subsequent increase in evapotranspiration, as well as rainfall and a peak in the growth cycle for bermudagrass. The highest N uptake was observed in response to CAS-7.5 and the lowest N uptake was observed in response to uncoated KNO_3 .

Coating thickness among the AS treatments also affected N uptake. The CAS-7.5 treatment produced a higher N uptake compared to CAS-15 and uncoated AS. However, no differences in N uptake were detected as a result of coating for the urea and KNO_3 treatment groups.

Third Treatment Interval. Results for the final treatment interval showed that overall N uptake for this period was generally higher when compared to the first and second treatment intervals, and in particular higher than the first

treatment interval. These N uptake results differ when compared to the N uptake data for 1992. One explanation is that, because rainfall was lower during the 1993 growing season leaching was reduced and therefore there remained an available N pool for the bermudagrass.

Nitrogen uptake data for this period revealed no differences between coated and uncoated materials within the AS and KNO_3 treatment groups. However, analysis of bermudagrass receiving the urea treatments revealed differences in N uptake between the two coated treatments and uncoated urea. Data suggests that the available N pool supplied by uncoated urea had been depleted or lost by this time in the experiment. There were no differences found among the different coating thicknesses within this group.

Overall, the uncoated materials produced higher N uptake during the 1993 growing season than during the 1992 season. This is probably the result of lower rainfall and consequently reduced leaching of the uncoated materials. Furthermore, the N uptake pattern varied from that of 1992 as a result of the longer residence time of N in the root zone. Nitrogen uptake by the bermudagrass was higher in 1993 when compared to 1992. This can be attributed to the larger available N pool as a result of reduced leaching of the applied N.

Growth and N Uptake by Stolons and Roots

At the termination of this experiment, stolons and roots were collected and analyzed for N, and N uptake was determined

based on N content coupled with dry weights. A summary of these results is presented in Tables 6-14 and 6-15.

Table 6-14. Stolon and root dry weight, (gm lysimeter⁻¹) and root length (cm) of bermudagrass.

Treatment	Stolon Weight	Root Weight	Root Length
AS	14.80 a	3.44 a	4.67 a
CAS-7.5	14.06 a	1.44 b	4.00 a
CAS-15	15.18 a	1.59 b	3.83 a
Urea	10.74 a	1.10 b	3.67 a
CUrea-10.5	12.54 a	3.45 a	3.83 a
CUrea-21	12.17 a	1.65 b	4.17 a
KNO ₃	10.01 a	1.22 a	4.00 a
CKNO ₃ -3	8.04 a	0.71 a	3.00 a
CKNO ₃ -6	10.53 a	1.13 a	3.83 a

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

Nitrogen uptake in the stolons was affected by N substrate and coating. The lysimeters receiving the AS and coated urea treatments showed higher N uptake in the stolon biomass than the other treatments. The KNO₃ treatments produced the lowest N uptake among all of the treatments. This can be attributed to the high mobility of this N substrate in the soil profile. The uncoated treatments, with the exception of uncoated AS, produced the lowest N uptake by the stolons. These findings suggest that N supplied as AS

Table 6-15. Nitrogen uptake in roots and stolons (mg N lysimeter⁻¹) of bermudagrass.

Treatment	Root N Uptake	Stolon N Uptake
AS	23.1 a*	166.1 b
CAS-7.5	11.9 b	225.1 a
CAS-15	9.9 b	205.1 ab
Urea	9.3 b	100.6 b
CUrea-10.5	24.5 a	205.0 a
CUrea-21	9.2 b	176.8 a
KNO ₃	8.1 a	118.0 a
CKNO ₃ -3	5.3 a	125.5 a
CKNO ₃ -6	7.4 a	119.7 a

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

remained in the root zone longer and was taken up more readily than other forms of N in this lysimeter study. Furthermore, highly mobile uncoated urea and KNO₃ did not remain in the root zone long enough to increase stolon N uptake.

Nitrogen Concentration

Bermudagrass N concentration in response to treatments is summarized in Table 6-16. Nitrogen concentration was affected by N substrate, coating, and growth of the bermudagrass. Nitrogen analysis of plant tissue (TKN) showed that average N concentrations over the 90 day experimental period was highest for CAS-7.5 and C Urea-10.5 and lowest for CAS-15 and uncoated CKNO₃. Coating had an affect on overall N level

Table 6-16. Average N concentration of Tifgreen bermudagrass following each N application.

Treatment	1 st Application	2 nd Application	3 rd Application
AS	3.65 a*	2.78 b	3.62 b
CAS-7.5	3.29 a	3.23 a	4.02 a
CAS-15	2.27 b	2.58 b	3.27 b
Urea	3.59 a	2.83 a	3.28 b
CUrea-10.5	3.40 a	3.15 a	4.06 a
CUrea-21	2.77 b	2.97 a	3.54 b
KNO ₃	2.42 a	2.66 a	4.15 a
CKNO ₃ -3	2.31 a	2.81 a	4.00 a
CKNO ₃ -6	1.75 b	2.81 a	3.85 a

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅.

in the bermudagrass during the initial period of each treatment application. In general, the thinly coated materials within all three treatment groups had the highest N concentration initially but decreased over time. The coated materials maintained a more nearly constant N concentration over time. Less variation between the maximum and minimum N contents was observed for the coated treatments. Generally, the thinly coated materials produced a higher average N concentration in the bermudagrass than did the heavily coated materials. This is a result of the higher release rate of these thinly coated treatments compared to high coated and uncoated treatments.

Likewise, growth had an effect on N content throughout

each treatment interval. Generally, higher growth rates corresponded with lower N contents in grass clippings. This is probably because of the dilution effect, where the grass produced a larger quantity of biomass and thereby a lower N concentration.

Visual Quality Ratings

Visual quality ratings of the bermudagrass for the 1993 growing season are summarized in Table 6-17. Uncoated urea and AS produced a higher quality grass during the initial period of each treatment application. Although initial quality ratings for the uncoated materials were high, quality ratings deteriorated at a faster rate after application than quality ratings for the coated materials. Bermudagrass quality was high initially in response to CAS-7.5. Unlike the uncoated treatments, however, CAS-7.5 sustained a high quality bermudagrass throughout the experiment because of its slow-release characteristics. The KNO_3 treatments generally produced a lower quality bermudagrass throughout the experiment.

Leaching of Applied N

Quantity of applied N leached was lower during the 1993 growing season than in 1992 (Figs. 6-9 to 6-11). This is probably the result of fewer rainfall events and lower quantities of precipitation experienced during 1993. The reduction in leaching demonstrates the profound effect rainfall can have on leaching of applied N. Comparison of the

Table 6-17. Visual quality rating of Tifgreen bermudagrass following each N application.

Treatment	1 st Application			2 nd Application			3 rd Application		
AS	a 8.0	a 8.3	a 8.0	b 7.3	a 8.0	a 8.3	ab 6.7	ab 7.3	a 7.0
CAS-7.5	a 8.0	a 7.7	a 8.3	a 8.7	a 8.7	a 8.7	b 6.3	a 8.3	a 7.0
CAS-15	b 6.3	b 5.3	b 6.3	b 7.0	a 7.7	a 8.0	a 8.0	b 6.7	a 7.7
CV**	5	8	8	6	9	11	11	11	9
Urea	a 8.0	a 9.0	a 8.0	a 7.3	a 7.3	a 8.3	b 6.0	a 6.3	b 6.0
CUrea10	a 7.7	b 7.7	a 8.0	a 7.7	a 8.3	a 8.3	ab 6.7	a 7.3	a 7.7
CUrea21	b 6.7	c 7.0	a 7.7	a 7.3	a 7.3	a 7.7	a 7.3	a 8.0	a 7.7
CV	6	6	11	8	7	10	7	13	7
KNO ₃	a 7.7	a 6.7	a 6.0	a 6.0	a 5.7	a 7.3	a 6.7	a 7.7	a 7.7
CKNO ₃ -3	ab 6.7	a 6.3	a 6.0	a 6.0	a 6.3	a 7.7	a 6.3	a 7.7	a 6.3
CKNO ₃ -6	b 5.7	b 4.7	b 5.0	b 5.3	a 5.7	a 7.3	a 7.0	a 8.0	a 7.3
CV	9	10	10	6	10	8	11	7	11

*Mean values within a treatment group and column followed by the same letter are not significantly different according to LSD₀₅;

**CV=Coefficient of variance.

1992 and 1993 growing season results shows that leaching of N does not occur as a result of irrigation if calibrated to meet the evapotranspiration rates of the turfgrass. Rather, leaching of N is the result of water input which exceeds the requirements of the turfgrass and the water-holding capacity of the root zone.

Total amount of N leached from lysimeters receiving uncoated AS was 12.2%. Uncoated AS leached mainly in the form of $\text{NH}_4\text{-N}$ (8.7%), with the remaining 3.5% leached as $\text{NO}_3\text{-N}$. Uncoated urea leached in three different N forms, accounting for 9.5% of the total N applied. This included 2.5% in the form of urea-N, 3.8% in the form of $\text{NO}_3\text{-N}$, and the remaining 3.2% in the form of $\text{NH}_4\text{-N}$ (Figs. 6-9, 6-10, 6-11). Similar to results obtained for the 1992 growing season, coating reduced the leaching of applied N. The coated AS and coated urea treatments leached less than 2% of the total N applied, while the KNO_3 treatments leached more than the other two treatment groups. The amounts of N leached from lysimeters receiving uncoated KNO_3 , C $\text{KNO}_3\text{-3}$ and C $\text{KNO}_3\text{-6}$, were 24.7%, 16.9%, and 13% respectively. However, leaching was still lower than for the KNO_3 treatment group in 1992.

Total Recovery of Applied N

Recovery of applied N was generally higher during the 1993 growing season than in 1992. Nitrogen recovery in the bermudagrass, and leaching fractions are summarized in Figures 6-10, 6-11 and 6-12. Uncoated AS and CAS-7.5 had the highest

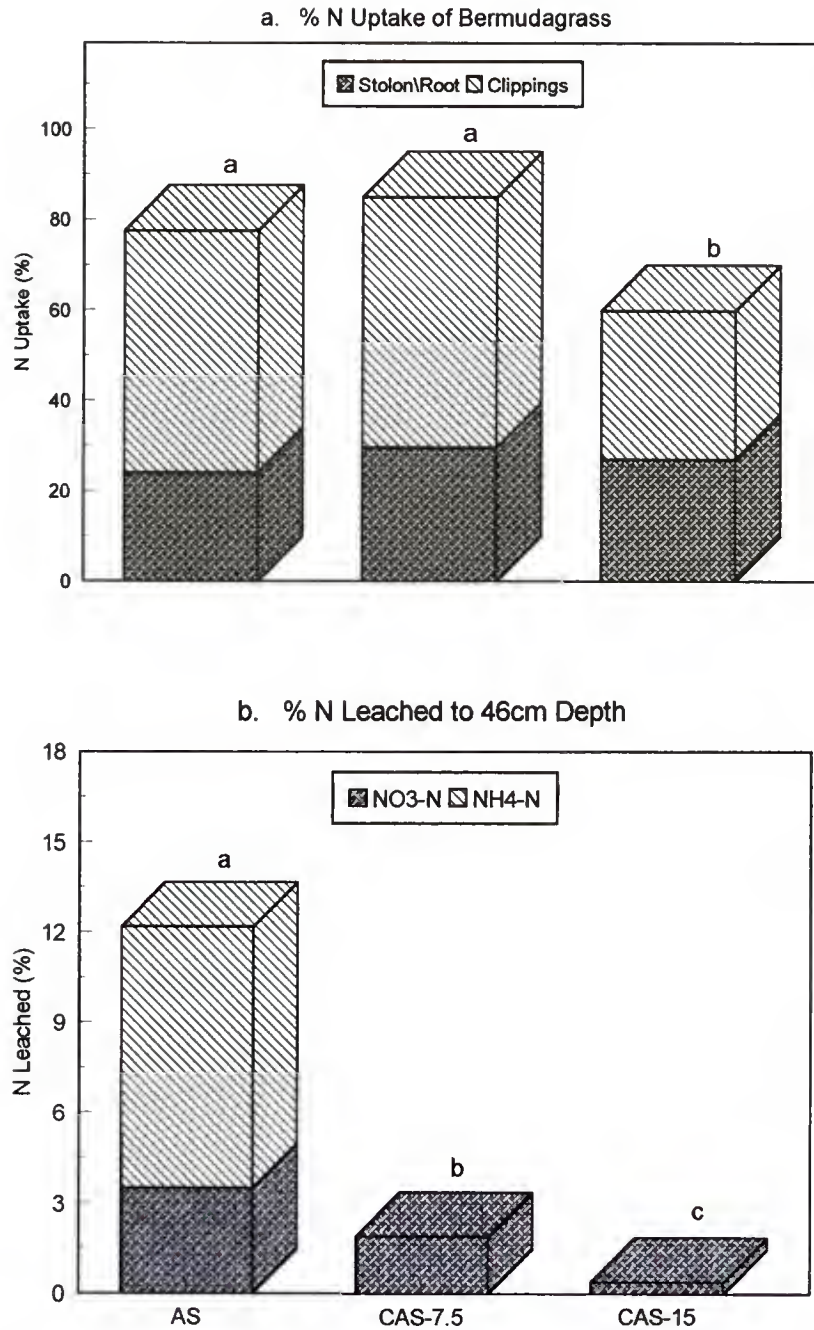


Figure 6-9. Nitrogen uptake and leaching recovery (1993): AS treatment group.

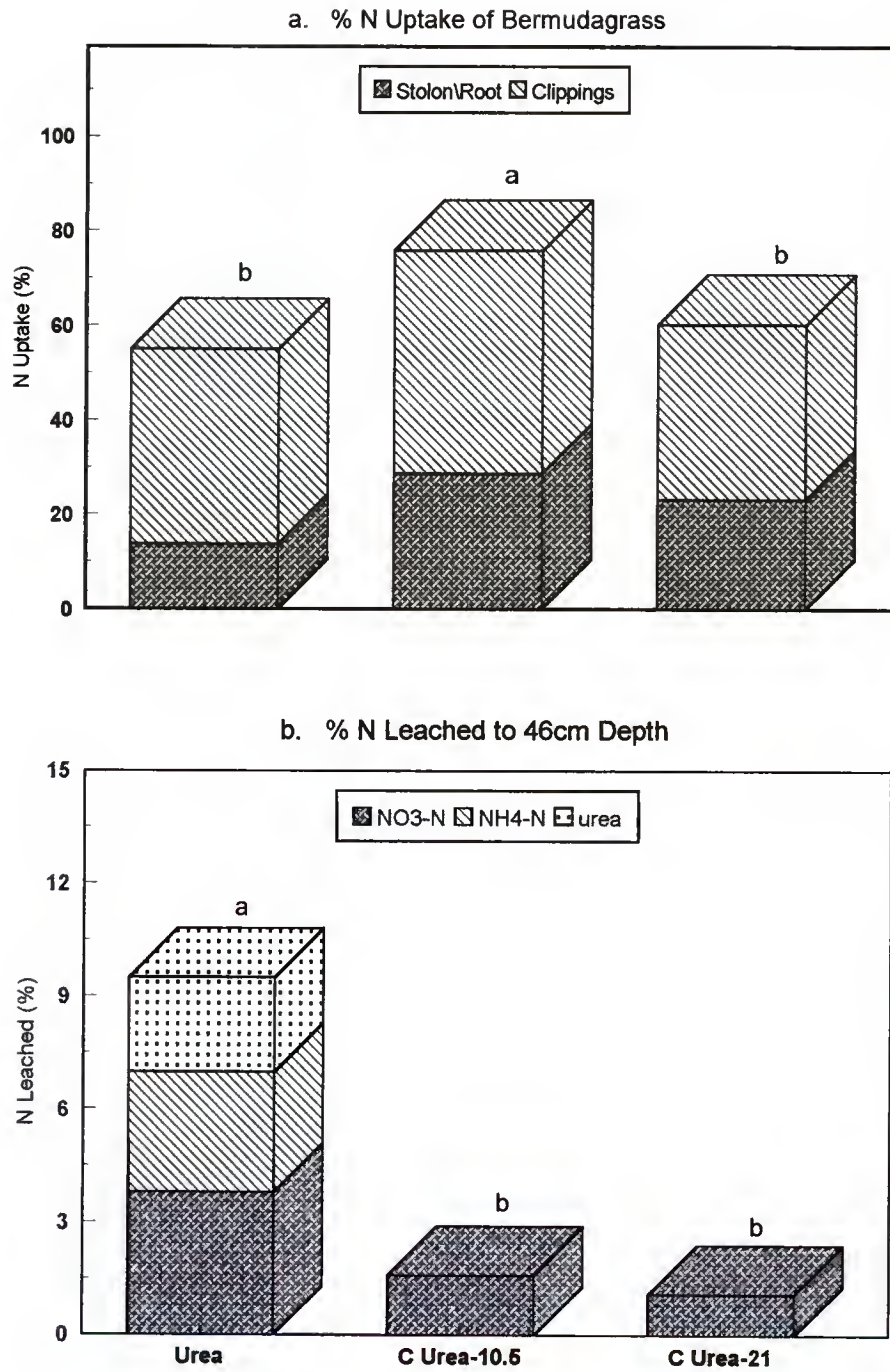


Figure 6-10. Nitrogen uptake and leaching recovery (1993): urea treatment group.

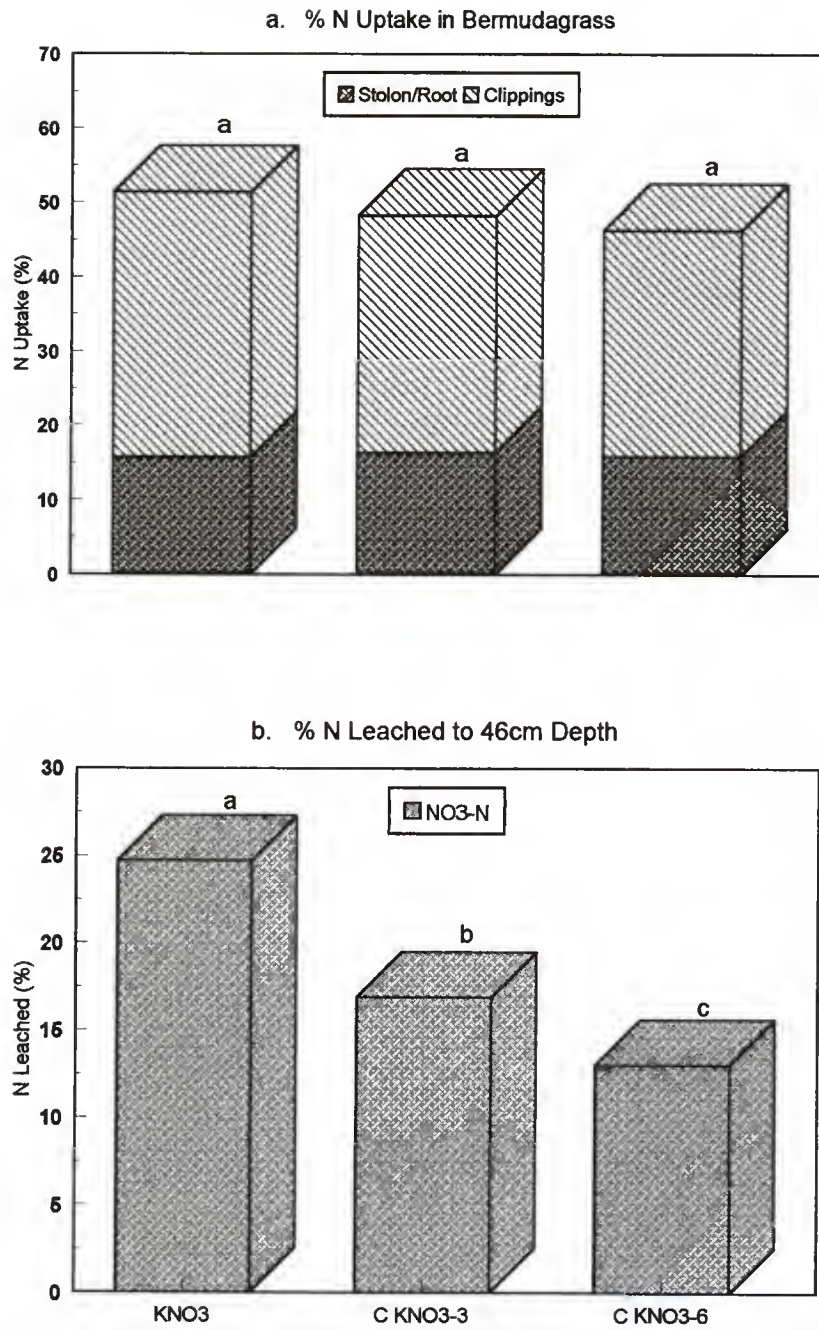


Figure 6-11. Nitrogen uptake and leaching recovery (1993): KNO_3 treatment group.

recovery rates, with 89.5% and 87% of applied N recovered. Coated Urea-10.5 followed, with 77.6% recovery of applied N. The percent recovery for uncoated KNO_3 was 76.1%, with 25% of this recovery in the leachate. Recovery of applied N for CKNO_3 -3 and uncoated urea were 65.2% and 64.4%, respectively. Similar to the recovery results for 1992, the thickly coated treatments had the lowest recovery of applied N. This could be attributed to the incomplete release of N from these coated materials.

Recovery of applied N was higher for the 1993 season compared to 1992, with the exception of CAS-15 and CKNO_3 -3. This was likely due to the lower rainfall experienced during the 1993 growing season. As a result of lower rainfall, N-uptake was greater and leaching losses were reduced. Rainfall events during this year did not induce large amounts of leaching, with the exception of one event in July which occurred soon after treatment application.

Summary and Conclusions

First year (1992)

This field lysimeter study was conducted from late May through mid August for the years 1992 and 1993. These months vary in temperature and rainfall. During May and early June, temperature and rainfall are generally lower than that experienced in late June through August. The months of July and August, on the other hand, are generally characterized by high temperatures and heavy rainfall in Florida. Irrigation was

maintained to meet evapotranspiration (ET) requirements of the bermudagrass. Therefore, water percolation to 46 cm was the direct result of rainfall events. During the 90 day period, rainfall pattern varied for each treatment interval. Total water percolated through the lysimeters during the 90 days was 69.5 cm. However, water percolated during this time frame was not distributed evenly, due to varying rainfall patterns. During the first treatment interval 18.8 cm of percolate was collected. The amount of water percolated in the second treatment interval was considerably higher, at 31.5 cm, due to increased rainfall during this time frame. During the third and final treatment interval, 19.2 cm of water percolated through the lysimeters.

Generally, the net effect on N leaching is the result of a combination of factors including rainfall, temperature, soil moisture and plant N uptake. The varying amounts of rainfall affected leaching directly and indirectly. Although the quantity of rainfall was much higher during the second treatment interval, increased rainfall also induced higher growth and N uptake by the bermudagrass because it coincided with the period of optimum growth within the annual bermudagrass growth cycle. Consequently, the increased growth and N uptake diminished the full potential of rainfall to leach the applied N. Furthermore, data for the first treatment intervals suggested that temperature was another factor affecting leaching of applied N. During the first treatment interval,

temperatures were generally lower and, therefore, growth of bermudagrass was lower, N transformation rates were slower, and release rates from the coated materials were slower. The combination of these factors resulted in less leaching of $\text{NO}_3\text{-N}$ during this treatment interval. Conversely, temperatures were higher during the second treatment interval, resulting in faster N transformations and faster N release rates from the coated materials. This resulted in more $\text{NO}_3\text{-N}$ available for leaching.

The results for N leaching showed the effectiveness of coating the N sources to varying extents depending on the coating thickness and N substrate. The total amount of $\text{NO}_3\text{-N}$ leached to the 46 cm depth was lowest from CAS-15 and C Urea-21, followed by C Urea-10.5. Concentration of $\text{NO}_3\text{-N}$ at the 46 cm depth for the above three coated materials was also well below the 10 mg L^{-1} $\text{NO}_3\text{-N}$ EPA standard. Although the amount of $\text{NO}_3\text{-N}$ leached from CAS-7.5 was higher compared to the above three treatments, the concentrations of $\text{NO}_3\text{-N}$ were still below the EPA standard with the exception of one sampling event, where a concentration of 10.2 mg L^{-1} was detected.

More $\text{NO}_3\text{-N}$ leached from uncoated urea compared to uncoated AS, because of the effect of initial increase in soil pH as a result of the hydrolysis of urea. This effect on pH increases microbial activity, which results in an increase in nitrification from the urea sources. However, this effect did not occur when the coated urea treatments were applied,

because the amount of N released was gradual and did not influence net nitrification.

The KNO_3 group had a higher amount of N leached, resulting in lower growth and N uptake compared to the other treatments. This was primarily due to the uncoated $\text{Ca}(\text{NO}_3)_2$ blanket application along with the nitrate substrate. Generally, nitrate fertilizers have higher leaching potentials because the NO_3 ion possesses a negative charge, which results in a higher mobility of this anion through the soil profile. Therefore, concentrations of $\text{NO}_3\text{-N}$ were well above EPA standards at the 46 cm depth. However, application of $\text{CKNO}_3\text{-6}$ reduced $\text{NO}_3\text{-N}$ concentrations by 48.1% at this depth compared to uncoated KNO_3 . Furthermore, $\text{CKNO}_3\text{-6}$ reduced the total quantity of $\text{NO}_3\text{-N}$ leached to the 46 cm depth by 46% compared to uncoated KNO_3 .

Second year (1993)

Total growth and N uptake were higher for uncoated urea and AS during the second year of the experiment. This is due to the larger available N pool, resulting from lower rainfall experienced during 1993 (44.6 cm) compared to 1992 (69.5) and consequently lower N leaching losses. Of significance is the fact that total N uptake and growth for the coated urea, AS and KNO_3 treatments were almost identical for both years. However, the growth and N uptake patterns varied each year because, of variations in the frequency and amounts of rainfall.

This study documents the reduction in leaching of N and

subsequent increase in N uptake and growth when polymer-coated material are utilized. Leaching data showed that the amount and form of N leached were the direct result of N substrate and coating. In addition, rainfall and temperature also affected the amount of N leached through the profile, and consequently growth and N uptake.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Understanding the fate of applied N fertilizer in a turfgrass environment is essential for maintaining quality turfgrass while protecting the groundwater. Utilization of controlled-release N fertilizers, as a management tool, provides an extended supply of N to the plant while reducing potential losses of applied N to the environment. Four studies were conducted to investigate the effectiveness of polymer coated AS, urea and KNO_3 with varying coating thicknesses in increasing plant uptake and decreasing N leaching.

Chapter 3 discusses the effect of temperature and coating on rate and amount of N release investigated under laboratory conditions. The following results were obtained:

1. Rate and amount of N release were increased when temperature was increased. An increase of 10 °C in temperature resulted in an increase ranging from 3% to 50% in percent N released. The increase in temperature increased solubility and diffusion of the N substrate, resulting in enhanced release of N.

2. Nitrogen substrate also affected the rate and amount of N released from the coating. The urea treatments had an overall higher N release than the other treatments. This can

be attributed to the higher solubility of urea compared to the other N substrates.

3. Particle size of the materials also affected N release, as well. The macro-size materials had a lower N release than the micro-size materials. This can be attributed to the larger surface area of the micro-size materials.

4. Increasing coating thickness resulted in a decrease in the rate and amount of N released. The magnitude of this decrease varied according to N substrate and temperature.

Chapter 4 presents findings on the effect of coated AS and urea on growth, N-uptake and visual quality of bermudagrass under field conditions. The following results were obtained:

1. During the first year of this experiment, growth and N uptake by bermudagrass increased as a result of coating with, the exception of CAS-9.8. Data collected from plots receiving CAS-9.8 revealed that, if coating is too thick, growth and N uptake will be retarded. While initial growth and N-uptake were high for the uncoated materials, they waned in the latter part of the experiment.

2. Visual quality of bermudagrass was improved by coating the N substrates. Although initial responses of bermudagrass were high in response to the uncoated materials, visual quality diminished over time. However, the coated materials produced a high visual quality that was consistent over time, with the exception of CAS-9.8.

3. During the second year of the experiment growth and N uptake responses to the urea treatments were the same as observed in the first year, with the exception of C Urea-12. The increase in the urea coating from 10% to 12% apparently resulted in a decrease in growth and N uptake. This is similar to the reduction in growth and N uptake observed in response to CAS-9.8.

In chapter 5, the fate of polymer coated ^{15}N labeled AS and urea was discussed. The open-ended lysimeter study focused on N uptake and leaching of applied N, and documented the concentrations of $\text{NO}_3\text{-N}$ in the Intermediate Vadose Zone and saturated zone. The following results were obtained:

1. During the first year of the study, coating AS and urea resulted in lower growth and N uptake during the initial period of the experiment when compared with the uncoated N substrates. However, this also resulted in a more uniform growth and N uptake over time. In addition, the gradual supply of N to bermudagrass in lysimeters receiving these coated materials produced a higher quality turfgrass for an extended period of time, with the exception of CAS-9.8. Coated AS-9.8 failed to produce the same results as the other coated materials, apparently because the 9.8% coating impeded the release of this N substrate. Coated Urea-10, on the other hand, produced growth and N uptake similar to that of C Urea-4.8. Differences between these two heavily coated N sub

strates can likely be attributed to the higher solubility of urea and consequent higher rate of release.

2. Coating the N substrates also affected leaching of N and concentration of $\text{NO}_3\text{-N}$ in the soil profile. The concentration of $\text{NO}_3\text{-N}$ was reduced as a result of coating. However, the effect of coating on $\text{NO}_3\text{-N}$ concentrations in leachate from lysimeters receiving AS and urea with the same coating thickness differed in magnitude. This is probably a result of the higher solubility of urea and therefore a higher rate of release.

3. The maximum $\text{NO}_3\text{-N}$ concentrations in the unsaturated zone (30 cm) was 189 mg L^{-1} and 169 mg L^{-1} in leachate from lysimeters receiving uncoated AS and urea, respectively. The maximum $\text{NO}_3\text{-N}$ concentrations detected in leachate at this depth from lysimeters receiving CAS-4.7 and C Urea-4.8 were 17 mg L^{-1} and 117 mg L^{-1} , respectively, while corresponding maximum $\text{NO}_3\text{-N}$ concentrations for CAS-9.8 and C Urea-10 were 9 mg L^{-1} and 33 mg L^{-1} . This demonstrates the effect that coating has on $\text{NO}_3\text{-N}$ concentrations at this depth. These concentrations can be used as an indicator of the relative release rates of N applied to turfgrass.

4. Concentrations of $\text{NO}_3\text{-N}$ at 120 cm (the water table level) for all treatments were lower than those detected at the 30 cm depth. However, $\text{NO}_3\text{-N}$ concentrations exceeding the 10 mg L^{-1} standard set by the EPA were detected for all treatments except CAS-9.8. The spikes in $\text{NO}_3\text{-N}$ concentrations from

uncoated AS and urea and from C Urea-4.8, corresponded with heavy rainfall events. Nitrate concentrations exceeding 10 mg L^{-1} for the remaining treatments were infrequent and only slightly above the EPA standard. Based on these findings, it can be concluded that coating N reduces N leaching. However, under heavy rainfall/irrigation, leaching may still occur as coating thickness decreases.

5. Recovery of applied N in the turfgrass/soil system, calculated using the tracer method, ranged from 27% to 71.5%. Coating increased recovery of N with the exception of CAS-9.8. This appeared to be a result of higher N recovered in the plant, as well as a decrease in N losses compared to the uncoated materials.

6. Recovery in the top 2.5 cm (thatch/soil) was higher than detected at lower depths (2.5 cm to 15 cm) within the soil profile. This demonstrates the significance of the thatch layer in the fate and retention of applied N.

7. During the second year of this lysimeter experiment, N uptake and growth of bermudagrass were higher for all treatments with the exception of CAS-4.7. Uncoated AS and urea produced twice as much N uptake and growth when compared with results from the first year. These results can be attributed to lower rainfall amounts and frequency experienced during the 1993 growing season. As a result, no leaching of applied N occurred, extending the availability of N in the root zone for uptake by the plant.

8. Coating the N substrate effected the recovery of residual N in the second year. Overall recovery was higher for the coated materials in the second year. This may be attributed to unreleased N from the first year, as indicated by highest recovery of CAS-9.8 in the second year.

Chapter 6 discusses N-uptake and leaching as affected by polymer coated micro-size AS, urea and KNO_3 applied to bermudagrass grown in lysimeters packed with USGA golf-green profile. The following results were obtained:

1. Nitrogen uptake and growth were effected by coating and N substrate. Uptake was higher for the coated urea and KNO_3 materials when compared with the uncoated treatments. This was also true for CAS-7.5. However, CAS-15 produced N uptake similar to that of uncoated AS. This can be attributed to the heavy coating and low solubility of this material. The gradual release of N from the coated materials allowed for longer residence time of N in the root zone for plant uptake.

2. Nitrogen concentrations in plant tissue remained relatively constant throughout the experiment in bermudagrass receiving the coated materials. This can be attributed to the more gradual release of N supplied to the plant.

3. Leaching was high for the uncoated treatments (21% to 46% of the applied N). This is due to several factors including: the soluble nature of the uncoated treatments, heavy rainfall experienced during the experiment, and rapid movement of N through the sandy USGA golf green profile.

However, coating these materials drastically reduced the amount of N leached.

4. Data revealed an inverse relationship between leaching and N uptake, in general. As leaching decreased as a result of coating, N uptake increased. However, this increase was not proportionate to the increase in coating thickness. Both coating thicknesses produced similar uptake within each treatment group.

5. During the second year of the experiment an increase in N uptake and growth and a decrease in N leaching were observed. This can be attributed to the lower rainfall experienced during this year. Lower rainfall had a greater impact on uptake and leaching in lysimeters receiving the uncoated materials.

Nitrogen fertilization is essential for establishing and maintaining quality turfgrass. Through proper N management, the quality of turfgrass can be maintained without threat to the environment. Advances in fertilizer technology make it possible to prolong the supply of N to the turfgrass without the need for elevated and frequent N fertilization. Controlled-release N fertilizers optimize the supply of N to the turfgrass by reducing N losses and regulating the release of N for plant uptake.

APPENDIX
WEATHER DATA

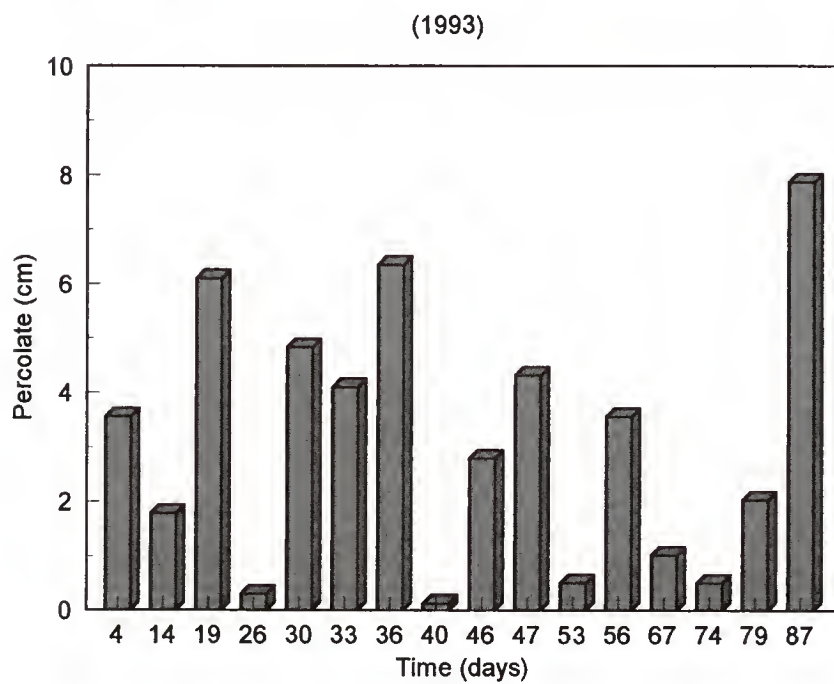
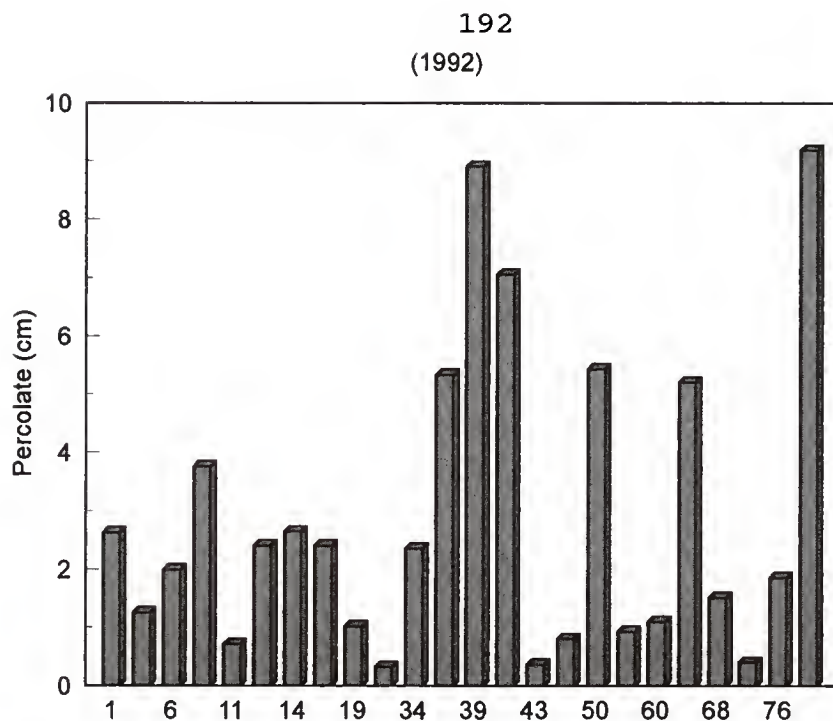


Figure A-1 & A-2. Rainfall and irrigation percolated to the 46 cm depth.

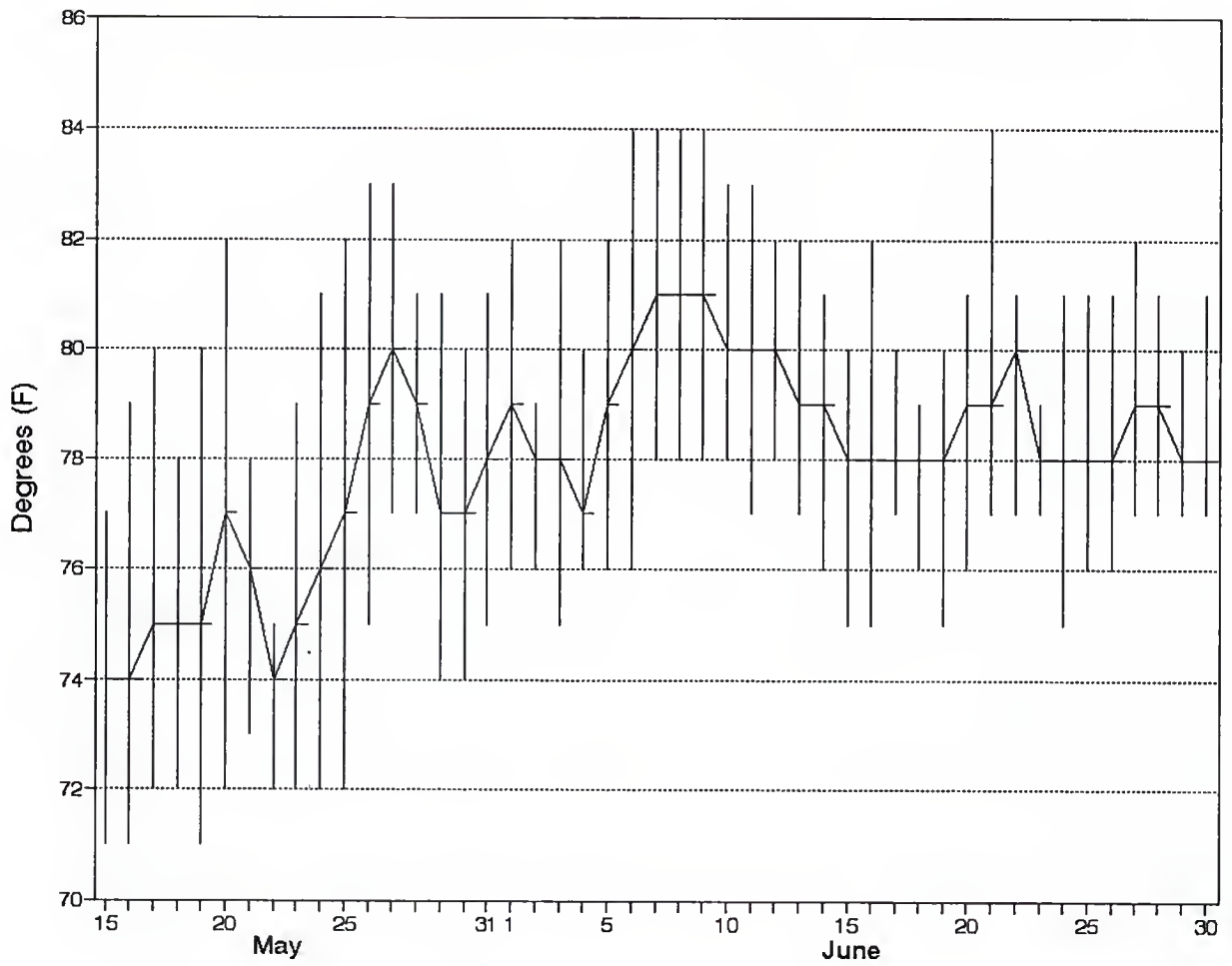


Figure A-3. Soil temperature for May and June (1992).

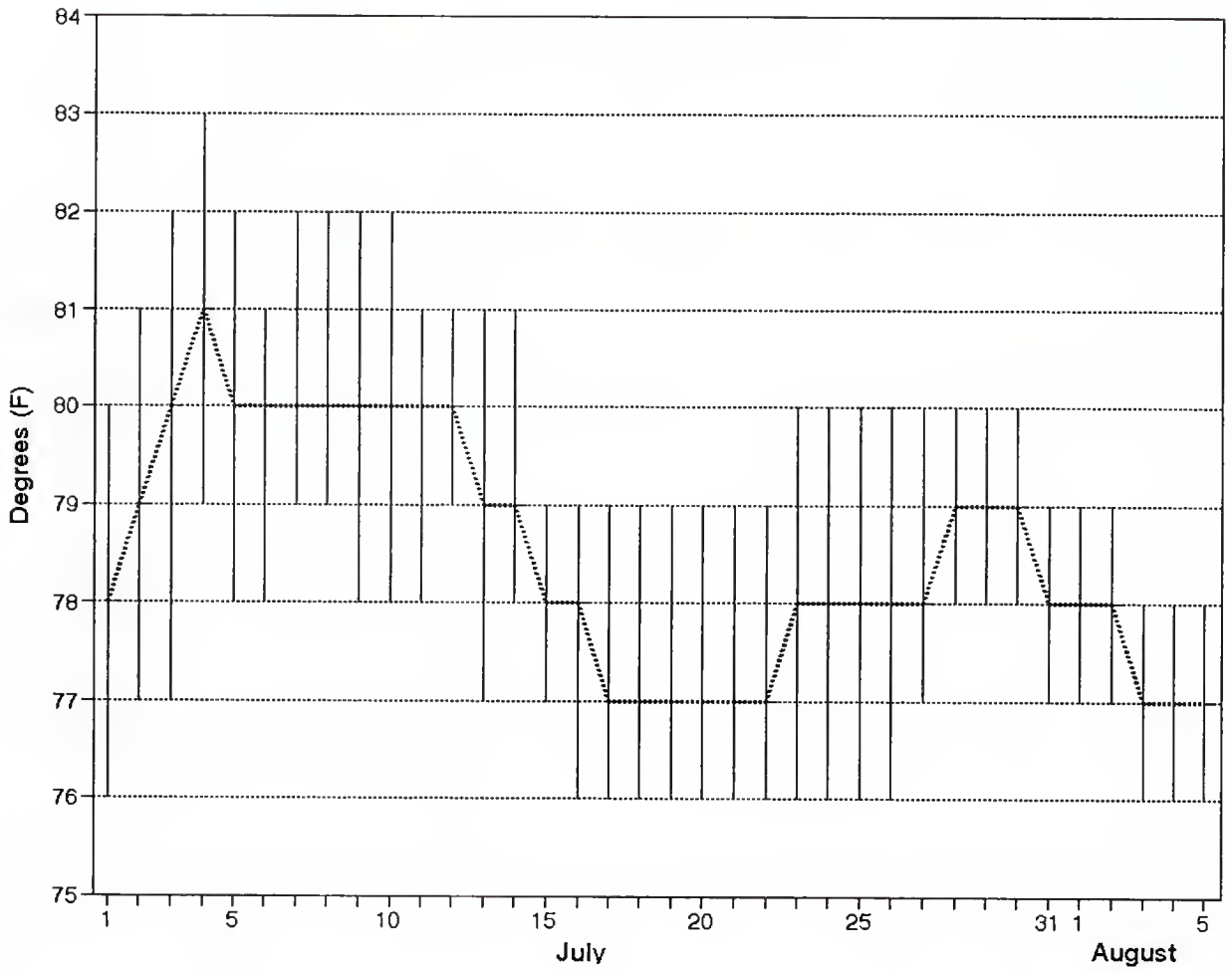


Figure A-4. Soil temperature for July and August (1992).

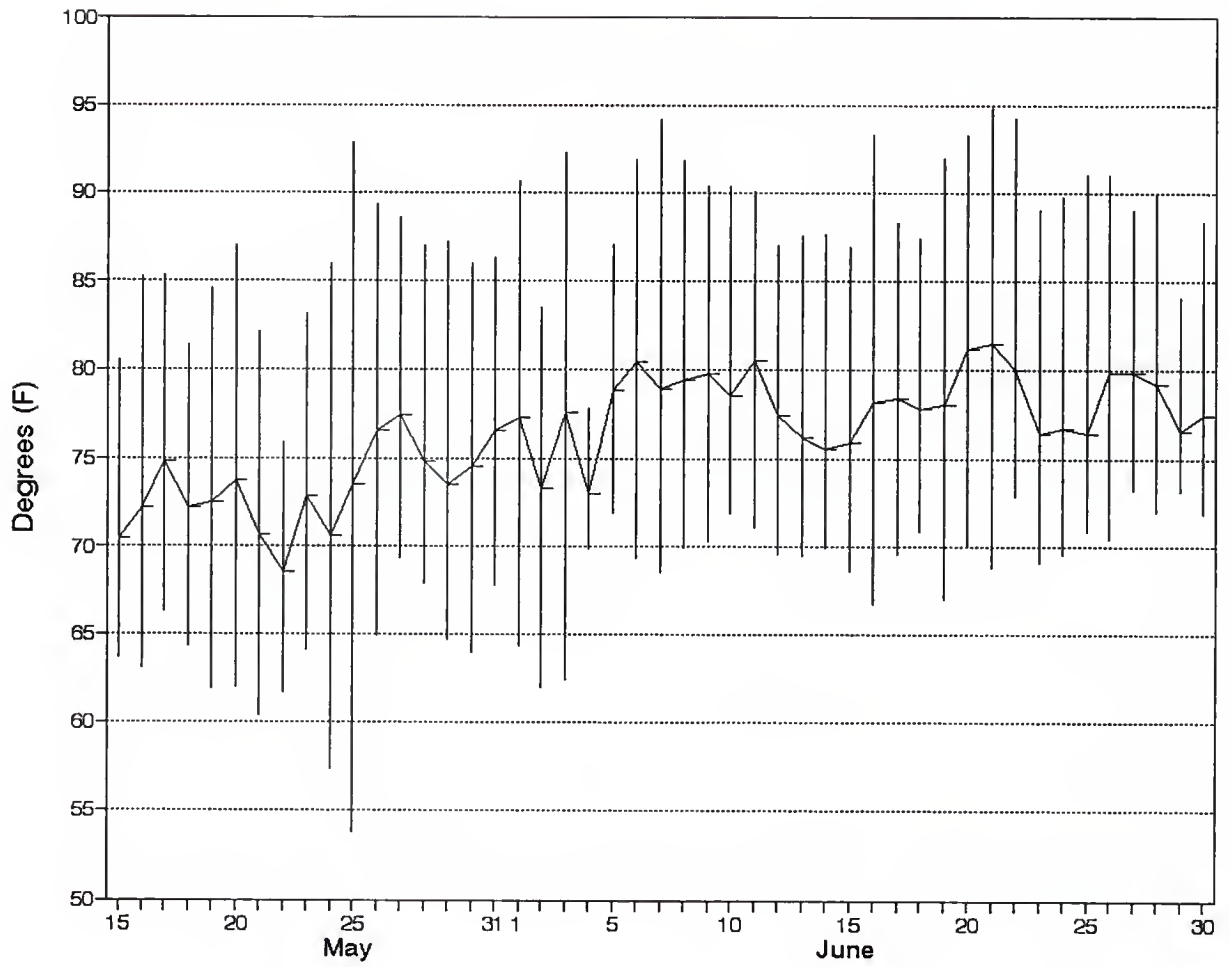


Figure A-5. Ambient temperature for May and June (1992).

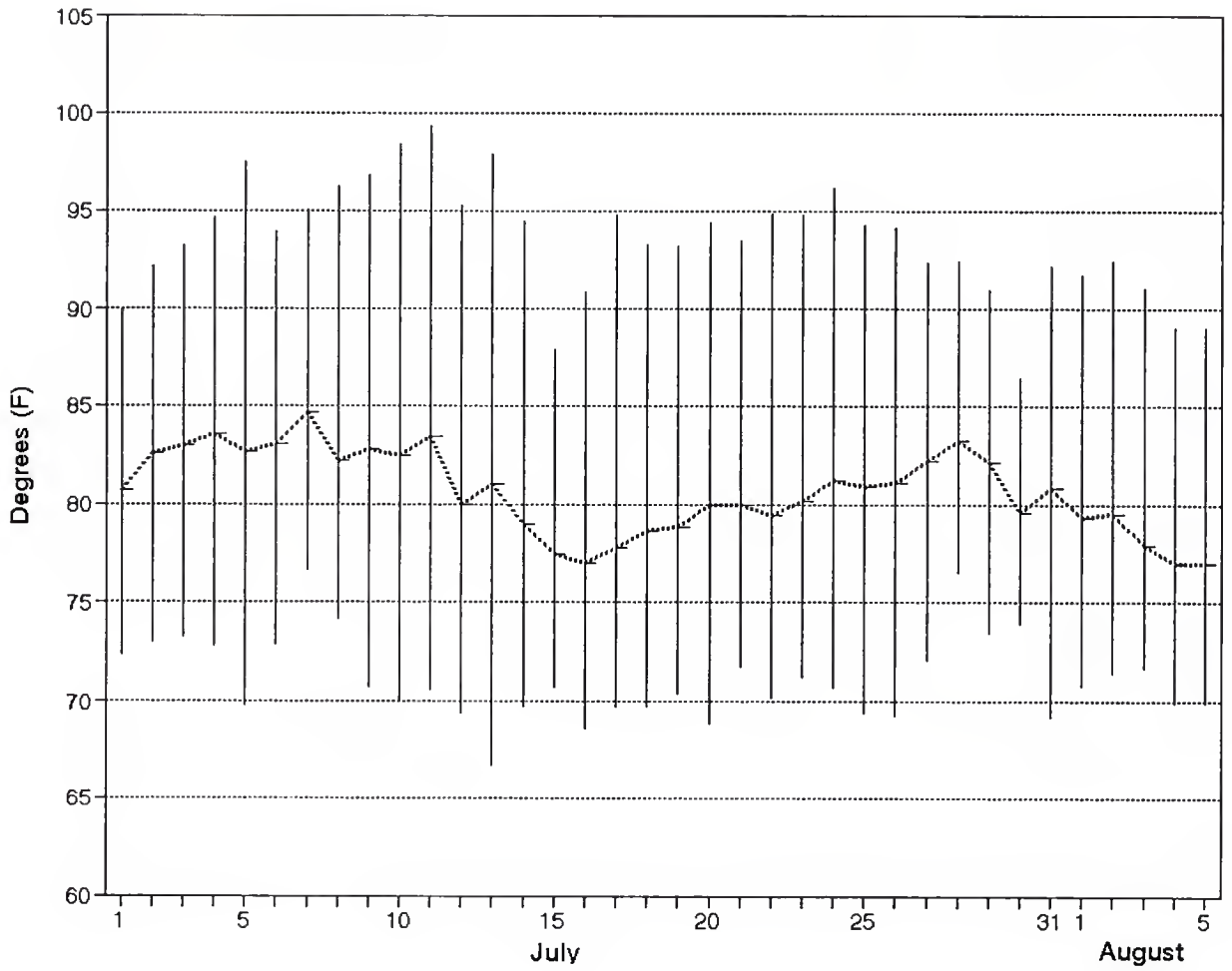


Figure A-6. Ambient temperature for July and August (1992).

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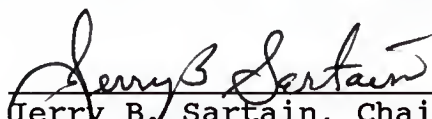
BIOGRAPHICAL SKETCH

Amir Varshovi was born in 1952 in the city of Abadan, Iran. After graduating from high school in Abadan, he came to the United States in 1972 to continue his education. He received his Bachelor of Arts degree in chemistry from the University of South Florida in 1977. He then returned to Iran, working in a cement plant as a chemist until 1979, and as a production supervisor until 1984. At that time he decided to return to the United States and reside in Gainesville, Florida.

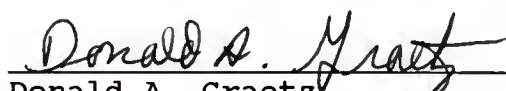
After working for a local environmental consulting firm (CH2M Hill) for two years, he joined the Soil and Water Science Department of the University of Florida in 1986, as a chemist. In 1988, Mr. Varshovi decided to pursue a graduate degree in soil science while continuing his full-time employment at the University of Florida. He received his M.S. degree in 1991 and continued with graduate studies towards a Ph.D. in soil and water science.

Amir is married to Nahid Menhaji, and they have two sons, Alexander and Zakariya.

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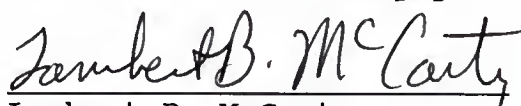
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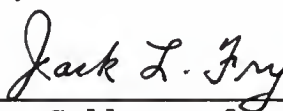
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This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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